MODELING AND CHARACTERIZATION OF POLYMER-FILLED HONEYCOMB COMPOSITES FOR USE IN ADAPTIVE STRUCTURES

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Abstract

Polymer-filled honeycomb composites (HPCs) consist of a polymer embedded into a honeycomb matrix. Previous research has shown that HPCs can exhibit a stiffness that is 100x greater than the honeycomb or polymer alone. However, the relative importance of the polymer properties, honeycomb geometry, and deformation characteristics on the composite behavior is not well understood. Limited experimental work has been completed for this reason, but the results have not been sufficient to aid in design or optimization problems. Current analytical models are either limited in their range of polymer to honeycomb stiffness ratios, or by the composite deformation. The aim of this research is to develop analysis tools and perform numerical studies to gain insight into the behavior of honeycomb composites. Linear and nonlinear finite element models were created to determine the effective in-plane properties of HPCs, and parametric studies have been completed on rigid wall unit cell model. Results demonstrate the importance of the polymer to honeycomb stiffness ratio and honeycomb geometry on the performance of HPCs. This work represents an important step in characterizing HPCs, and may aid in future experimental studies and design problems.

Introduction

Existing space structures often rely on mechanical linkages, hinges, and joints for deployment once in space. These mechanisms are typically passive, meaning they are unable to vary their mechanical properties to suit their application. The complexity and weight of current structures requires a need for lightweight and robust designs that allow for easy deployment and reconfiguration through control of the structures' mechanical properties. Smart materials that can vary their mechanical properties are well suited for this need.

Smart materials are characterized by their ability to alter their properties in response to an environmental stimulus. An example of a smart material is a shape memory polymer (SMP), which is a class of smart materials that exhibit a relatively low stiffness, but can achieve changes in stiffness of over three orders of magnitude through temperature variation[123]. The stiffness and shape changes seen in SMPs are desirable for creating novel structures, and can be advantageous when used as core materials in cellular composites.

Previous research by the PI has shown that honeycomb-polymer composites (HPCs), which rely on an aramid honeycomb with polymer core materials (see Figure 1), exhibit a stiffness that is 100x greater than the honeycomb or polymer alone.

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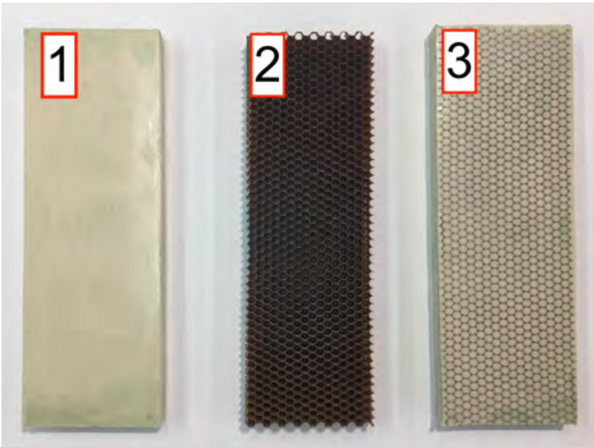

Figure 1. HPC diagram. Polymer in (1), unfilled aramid honeycomb in (2), and polymer-filled honeycomb composite in (3).

Lightweight and adaptive structures can now be realized using shape memory polymers and advanced additive manufacturing to create programmable multifunctional lattice composites that are capable of significant stiffness and shape changes for deployable space structures. Before these structures are feasible, however, it is first necessary to better understand HPCs and how the material properties and cell geometry affects their performance.

Current Models and Limitations

There exist several models in the literature for capturing the elastic deformation of unfilled honeycombs, including that by Master and Evans that relies on three modes of deformation of the cell walls[4]. In this model the deformation is assumed to be a superposition of the hinging rotation of the cell walls, the flexing within the walls, and axial displacement of the walls. The effective axial deformation and modulus of the honeycomb is then determined through a summation of the three modes.

While this model has been found to work for unfilled honeycombs, it is not capable of modeling the polymer-filled honeycomb. The earliest effort to model honeycombs with an infill material was reported by Abd El Sayed[5]. This uses a strain energy approach to determine the work done on composite. It assumes perfect bonding between the cell walls and infill materials, and that the cell walls are rigid. Though found to be accurate, it is generally only applicable for polymer stiffness's four orders of magnitude less than the wall stiffness. Other models have followed from this work, but all retain the limitations.

Recently there have been attempts to correct the aforementioned shortfalls, by such methods developed by Beblo et al[6]. In this work, the honeycomb is assumed to carry the majority of the load, with the infill acting to stiffen the cell walls against rotation. This model is advantageous in that it allows for the determination of several in-plane elastic constants that are necessary for optimization. The results of this model are found to be an improvement upon the earlier work on filled honeycombs, but the accuracy of the model as the infill modulus approaches that of the honeycomb is still present.

Based on the state of current models, there is a need to be able to predict the mechanical properties of honeycomb composites with polymer infill stiffness's that are of equal or greater magnitude to the honeycomb itself. Therefore the goal of this research is to develop numerical tools and perform studies on honeycomb structures with a polymer infill. The approach is to employ finite element tools to model the honeycomb structures assuming rigid walls and deformable walls.

Finite Element Modeling

Prior to describing the numerical studies, we first define the chosen HPC geometric parameters and coordinate system. The geometry of a HPC unit cell may be defined using four parameters, depicted in Figure 2. These are the wall thickness, (t_w), wall length, (L_w), cell depth, (D), and the cell angle, (θ). Additionally, the cell walls and polymer infill are considered to be isotropic with respective Young's moduli and Poisson's ratios.

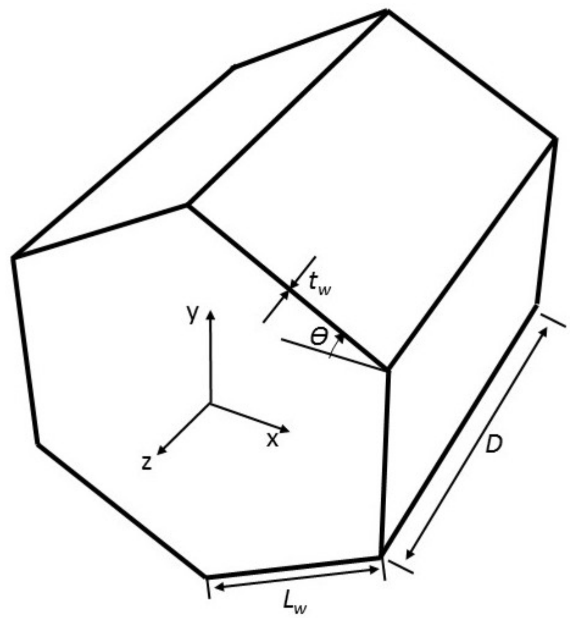

Figure 2. Definition of unit cell geometry.

For this current research it is desirable to determine an upper bound on the stiffness amplification of HPCs. This will provide an indicator of the degree to which the polymer stiffness deforms the cell walls and decreases the stiffness amplification from the honeycomb. For this reason, a rigid cell wall model was created with pinned hinges, with the rigid walls being modeled using discrete rigid bodies and applied boundary conditions. From this the three modes of honeycomb deformation are neglected, and the honeycomb has no inherent modulus and only serves to amplify the polymer stiffness. A cross section of this model is shown in Figure 3, where degrees of symmetry about the *x* and *y* axes are leveraged to reduce the model's size.

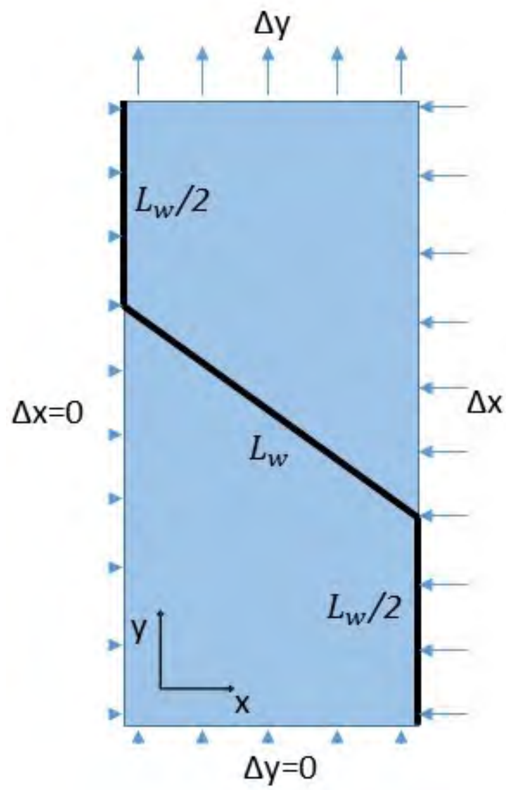

Figure 3. Cross section of unit cell rigid model and boundary conditions.

The unit cell was prescribed an axial deformation in the form of a change in the cell angle, $\Delta\theta$. Due to the rigid cell walls, the rigid body in-plane displacements and rotations of the cell walls are known for a given $\Delta\theta$, and are expressed in Eqs. (1) and (2) below.

$$\Delta x = L_w[\cos(\theta + \Delta\theta) - \cos(\theta)] \quad (1)$$

$$\Delta y = L_w[\sin(\theta + \Delta\theta) - \sin(\theta)] \quad (2)$$

Before parametric studies were completed, appropriate mesh sizes were determined through convergence studies. At nominal honeycomb parameters, the mesh size was varied, and the convergence of effective properties and the required computation time were compared. From these results, shown in

Figures 4 and 5, it was found that an approximate mesh length of 0.2mm was adequate for the analysis due to limitations of computation time and a convergence of the effective modulus for nominal parameters.

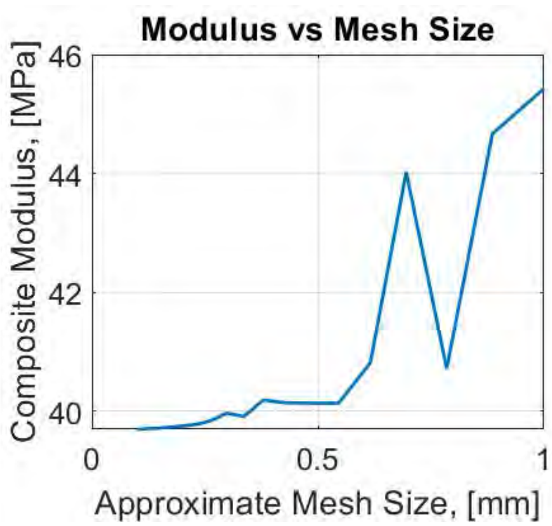

Figure 4. Effective modulus as mesh size is decreased. Note that at mesh size of approximately 0.2mm the modulus has converged.

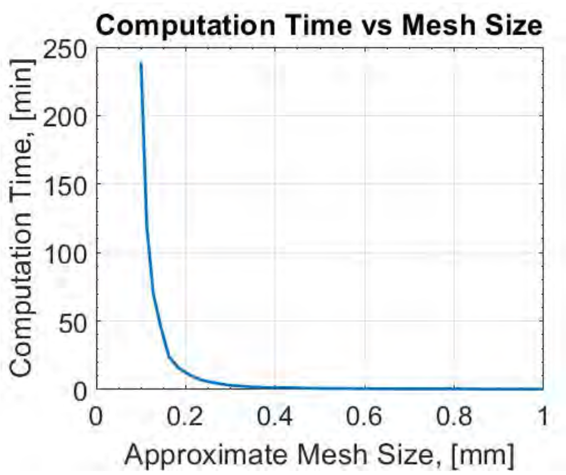

Figure 5. Computation time as mesh size is decreased. Note that after a mesh size of 0.2mm the computation time diverges and becomes impractical to solve.

Effective Property Methods

There exist several methods of determining the effective properties of composites from finite element analysis results. Currently, the effective modulus of the composite is obtained using a boundary method[7], where the homogenized stresses and strains are obtained from the nodal reaction forces and the prescribed end displacements. The equivalent axial strain was found using the defined deformation cases previously defined. The homogenized axial stress, $\bar{\sigma}_{ii}$, was found by summing the applied nodal forces, *F*, to obtain a point axial load, and divide by the cross sectional area as in Eq. (3) below:

$$\bar{\sigma}_{ii} = \frac{\sum_{j=1}^{N_{node}} F_j}{\bar{S}} \qquad (3)$$

$$where\ \bar{S} = mean\ cross - section\ area$$

Lastly, the effective modulus may be obtained from Hooke's law for a uniaxial loading:

$$E_i = \frac{\bar{\sigma}_{ii}}{\bar{\epsilon}_{ii}} \qquad (4)$$

Results

Rigid Honeycomb

Parametric studies have been completed for the rigid wall unit cell, with variations in the infill properties and the cell geometry being studied. First, consider the effect of cell angle and polymer infill modulus in Figure 6 below.

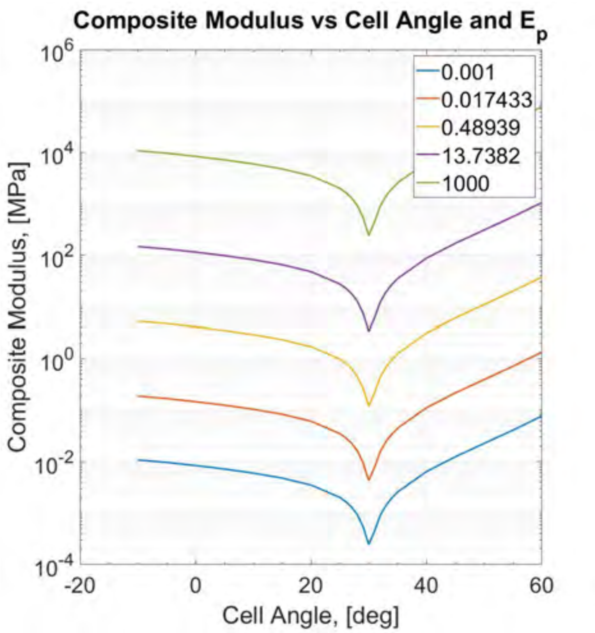

Figure 6. Composite modulus vs cell angle for constant values of polymer stiffness.

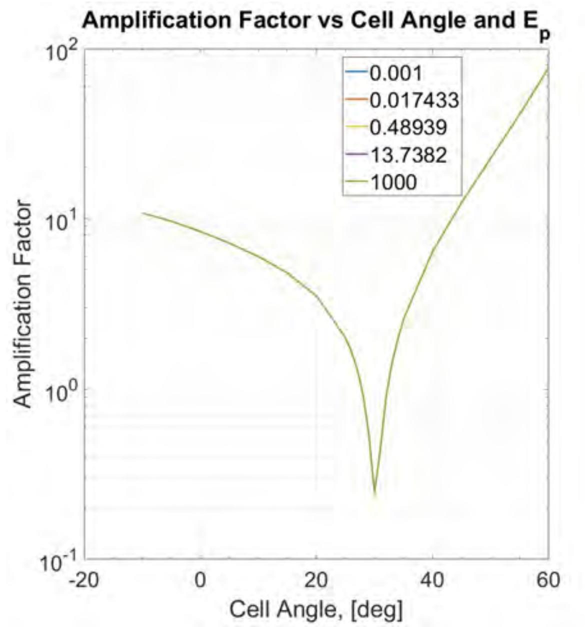

Figure 7. Amplification factor for varying cell angle at constant polymer stiffness.

Above we find that, as expected, increasing the infill modulus increases the effective modulus. It is seen that the trend in effective modulus for varying cell angles is also the same for any polymer modulus. Considering the dependence on cell angle, it is found that the minimum effective modulus occurs at 30^o. In previous work this has been expected and may be explained a minimum change in cell volume that occurs for deformation about 30^o. As the cell angle changes from this angle the effective modulus is seen to increase. Next we consider the amplification factor of the above results, a nondimensional parameter defined as the effective modulus normalized by the polymer modulus, seen in Figure 7.

Above we find that, for a rigid wall model, the amplification factor is independent of the polymer stiffness. This may be explained by the primary effect of increasing the infill stiffness amplification ratio: to increase the wall deformation and decrease the stiffness amplification of the honeycomb. This indicates that in an idealized model, the amplification ratio becomes constant with polymer stiffness. Next, consider the effect of the deformation, $\Delta\theta$, on the effective modulus, as found below in Figure 8 for varying cell angles.

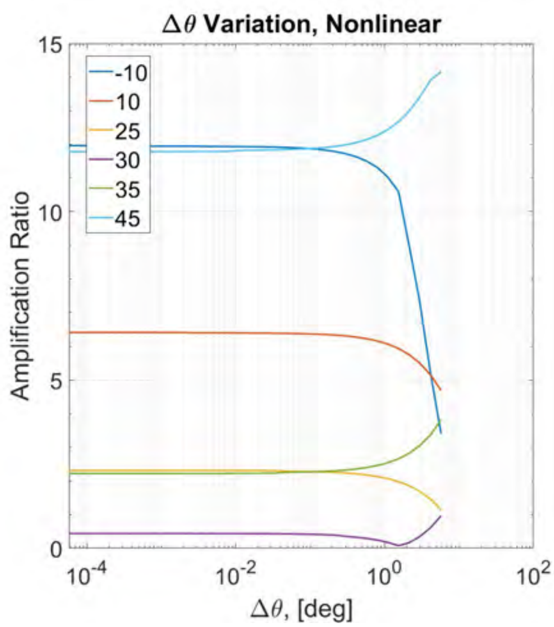

Figure 8. Nonlinearity of HPC materials as deformation changes.

In Figure 8 is it is seen that the effective modulus converges below a cell angles change of approximately 0.01^{o}, and above this point the measured amplification ratio diverges. The change in measured amplification ratio under tension is found to be related to the direction of change of the cell angle with respect to the minimum at 30^{o}. For initial cell angles below 30^{o}, the final cell angle approaches the minimum, the polymer amplification correspondingly decreases as the deformation increases. Likewise, above 30^{o}, the final cell angle after deformation increases away from 30^{o}, and the resulting amplification increases as was found for increases cell angles in Figure 7 previously. Next, the cell depth is varied, and a nondimensional parameter called the cell aspect ratio, defined as the cell depth normalized by the wall length, is used for plotting purposes. The results are found below in Figures 9 and 10.

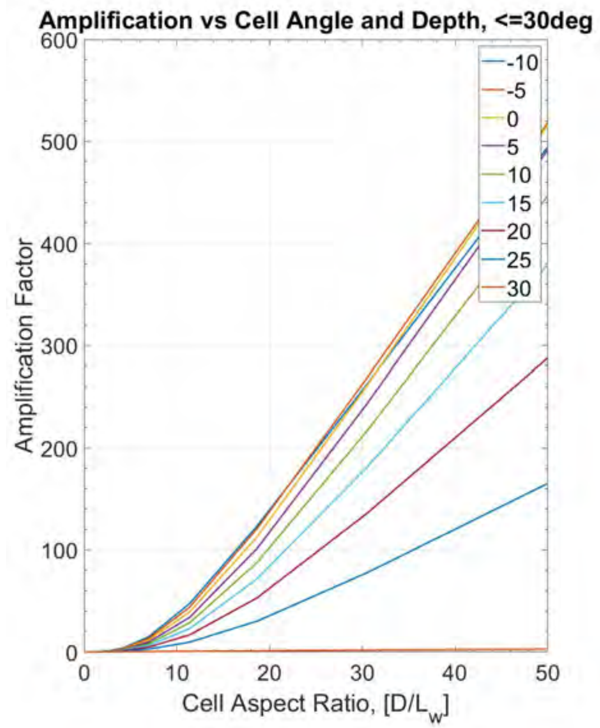

Figure 9. Effect of cell depth on amplification factor.

In Figure 9 above the results of varying the cell depth for cell angles below 30^{o} are compared. It is seen that as the cell aspect ratio increases, the measured amplification factor increases as well. The trend of increasing amplification factor as the cell angle moves away from 30^{o} is still observed. The increase in amplification is attributed to the proposed effect of the honeycomb on the polymer, namely a volume change applied to a nearly incompressible material that correspondingly resists this change and results in an increase in effective stiffness. The volume change of the honeycomb cell is accounted for by an out-of-plane deformation of the polymer out to the open ends of the cells. As the cell depth increases however, the assumed perfect bonding between the polymer and cell walls limits the degree of deformation, and further increases the observed stiffness and amplification.

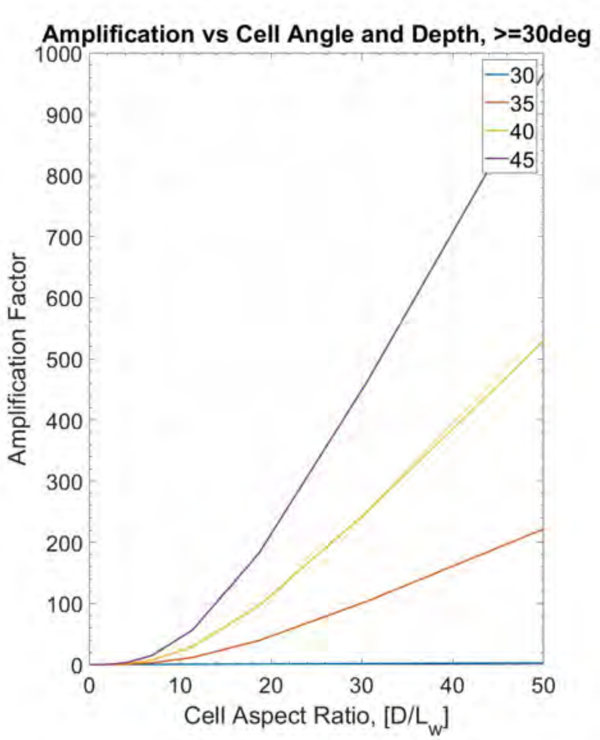

Figure 10. Effect of cell depth on amplification factor for cell angles above 30°.

Next, the amplification of cell angles above 30° are found for varying cell aspect ratios in Figure 10. Similarly to Figure 9, the amplification factor increases with increasing cell angle and cell aspect ratio. The more importantly, the amplification is seen to increase to up to 1000x the polymer stiffness at 45°, indicating a significant increase in stiffness of the composite in the axial direction.

Conclusions and Current Work

In this research, the design space of polymer filled honeycomb composites has been examined, with applications to deployable structures. A rigid cell model has been created and is currently undergoing parametric studies. Presently, we have noted that, for an idealized rigid model, the polymer stiffness does not affect the amplification due to the honeycomb. The previously proposed minimum amplification at a cell angle of 30° has been supported in all parameter studies thus far. There are observed nonlinearities in the HPC material, and under large deformations that observed stiffness changes significantly. Lastly, the cell aspect ratio plays an important role on the ability of the honeycomb to increase the effective stiffness by constraining the polymer under an applied volume change. Currently, parametric studies are being completed for the rigid unit cell, full-scale deformable model, and a deformable unit cell model. Additionally, a design optimization is being completed on a simplified deformable model subject to load conditions to simulate stowed and deployed cases for a space structure. Additive manufacturing and SMPs are not currently being considered for the design, but will be implemented later as performance metrics and design constraints. This ongoing research has provided insight into the performance of HPCs and has been a critical step in the future design and optimization of adaptable structures.

Acknowledgements

The author would like to thank the Aerospace Structures and Materials Lab for providing the equipment and resources to complete this work. Additionally, the author thanks the Virginia Space Grant Consortium for providing the necessary funding to support this research over the past three years.

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