FORMABLE SANDWICH CORES WITH NON-CONVENTIONAL CELL SHAPES

Steven Nutt and Changzheng Huang

Gill Foundation Composites Center
University of Southern California, Los Angeles, CA 90089-0241, USA
nutt@usc.edu, changzh@usc.edu

ABSTRACT

Conventional sandwich cores with hexagonal honeycomb cells generally exhibit high stiffness and low flexibility. However, for some applications, it is desired to have a formable core that can be formed to complex shapes. In this study, we investigate formable sandwich cores with non-conventional cell shapes. We develop a parametric model that can be used to generate a wide variety of cell shapes with non-straight cell walls. The equivalent mechanical properties of these formable cores are also studied.

1. INTRODUCTION

Sandwich structures are made of a light-weight core sandwiched between two thin face sheets. This type of construction can be designed to yield a high bending stiffness with minimal structural weight [1]. The most commonly used sandwich cores are conventional honeycomb cores in which the cell shapes are hexagonal and the cell walls are straight. The equivalent continuum medium properties of honeycomb cores are also well studied [2-5]. Gibson and Ashby derived classical formula for predicting core mechanical properties from the intrinsic properties of the core materials, as well as from the geometry of hexagonal unit cells [2].

Sandwich structures with conventional honeycomb cores are most often used as flat panels. Because they have high bending stiffness, they are not easily formed into curved shapes. In fact, when a honeycomb core is bent down in one direction, the core surface will curve up in the transverse direction (anticlastic bending), resulting in a saddle surface. Therefore, conventional honeycomb cores are not suitable for applications that require core formability, such as radar domes. For these applications, one may consider non-conventional sandwich cores that are less stiff but more readily formable.

Motivated by such application needs, we conducted this study on formable sandwich cores with non-conventional cell shapes with non-straight cell walls. Sandwich cores with curved cell edges are flexible and can be easily formed into complex shapes. Figure 1 shows one example of non-conventional core being formed into a spherical shape. Honeycomb cores with non-straight cell walls have not received much attention, although there are a few studies that have considered sinusoidal cell edges to explore the effect of cell wall distortion [6-8]. In contrast, we consider the cell edges to have a general shape of splines [9].

In the following, we first describe the model that is used to generate a wide variety of cell shapes. This is followed by an investigation of the equivalent core mechanical properties, especially the in-plane Young’s modulus and Poisson’s ratio. Conclusions are given in the last section.

2. GENERATION OF NON-CONVENTIONAL CORES

A non-conventional honeycomb core with non-straight cell edges is illustrated in Fig. 2. Honeycomb cores can be fabricated by laying up a stack of paper sheets printed with stripes of heat-activated adhesive. This is followed by heating under pressure to form the node bonds, mechanical expansion of the sheet stock to for the honeycomb cells, and finally, dipping in phenolic resin and curing.

A representative unit cell of the general honeycomb core is depicted in Fig. 3. Note that in the unit cell, edges *AB*, *CD*, and *EF* are node bonds. A node bond is a location where two adjacent layers of paper sheets are bonded together by adhesive. Therefore, a node bond has a double-wall thickness. The other two cell sides *BC* and *DE* are free edges that have only single-wall thickness. During the core expansion process, the node bonds and the free edges will undergo different deformations. The double-thickness node bonds have greater bending stiffness. Therefore, they may well stay as straight segments. In contrast, the single-thickness edges are much more flexible. They may be deformed into some general shapes in the expansion process. If the mechanical expansion is halted prior to reaching the full extent, then the free edges will retain their intermediate curved shapes, resulting in a core product that is similar to the core shown in Fig. 2. On the other hand, if the expansion is completed to its full extent, then the free edges will be nearly straightened. The resulting product is a regular honeycomb core.

To model non-conventional cores, it is reasonable to assume that the node bonds are straight and the single-wall edges are curved. In this study, we model this curved cell edge *BC* by a spline approximation,

$$y = a_3 x^3 + a_2 x^2 + a_1 x + a_0 \tag{1}$$

Here, a_i are coefficients that can be determined from the boundary conditions,

$$\begin{aligned} y\big|_{x=x_B} &= y_B, \left.\frac{dy}{dx}\right|_{x=x_B} = \tan\alpha \\ y\big|_{x=x_C} &= y_C, \left.\frac{dy}{dx}\right|_{x=x_C} = \tan\beta \end{aligned} . \tag{2}$$

Here, α and β are two slope angles at the end-points *B* and *C* respectively, as shown in Fig. 3. By changing the slope angles α and β, one can generate different spline curves for the cell segment *BC*.

For example, the non-conventional core depicted in Fig. 2 is generated with the following parameters. Suppose the width and height of the unit cell are denoted by *a* and *b*. The node bond lengths are, $|AB| = |EF| = h_1$, and $|CD| = h_2$. In this example, we consider a square-shaped unit cell and equal bonding length, i.e., $a = b$ and $h_1 = h_2 = h$. Furthermore, we take $h/a = 0.25$ and $\alpha = \beta = 45°$. This core is much like a core fabricated from an expansion process in which the pulling force was insufficient to straighten the cell edges.

By varying the parameters *a*, *b*, h_1, h_2, α, and β, one can obtain a wide variety of sandwich cores with non-conventional cell shapes. Regular honeycomb cores can also be generated as a special case from this model. Sandwich cores with curved cell walls are more flexible than conventional honeycomb cores, because the curved cell walls are more readily stretched or compressed under bending loads.

3. IN-PLANE PROPERTIES OF NON-CONVENTIONAL CORES

We now consider the equivalent continuum medium properties for non-conventional sandwich cores. Core properties such as the in-plane Young's modulus and Poisson's ratio are important for the prediction of core deformation and core formability. Properties of conventional honeycomb cores have been widely studied and analytical solutions are available [2]. However, analysis of sandwich cores with non-straight cell walls is more complex. Below we propose a numerical method for calculating the in-plane core properties.

To determine the x-direction Young's modulus E_x, an external stress is applied to the unit cell in the x-direction as illustrated in Fig. 4. As a result, the tips of the unit cell are displaced by a distance δ_{xx} in the x-direction and δ_{yy} in the y-direction. The strains are defined as the relative deformation of the unit cell,

$$\varepsilon_x = \frac{2\delta_{xx}}{a}, \varepsilon_y = \frac{2\delta_{xy}}{b}. \tag{3}$$

The x-direction Young's modulus E_x and Poisson's ratio μ_{xy} are computed as,

$$E_x = \frac{\sigma_x}{\varepsilon_x}, \mu_{xy} = -\frac{\varepsilon_y}{\varepsilon_x}. \tag{4}$$

The key in this computation is to evaluate the tip displacements δ_{xx} and δ_{yy}. Note that these displacements are caused largely by the deformation of the curved cell edge. This deformation can be analyzed by dividing the curved edge into multiple small segments. Each segment can be approximated as a beam element. The deformation for a straight beam element has analytical solutions. The deformation of the curved cell edge is the summation of the incremental deformation of all the beam elements. In this way, the tip displacement can be calculated. Subsequently, the x-direction Young's modulus E_x and Poisson ratio μ_{xy} can be evaluated from Eqs. (3) and (4).

As an example, consider the sandwich core shown in Fig. 2 again. Recall that the parameters for the unit cell are $h/a = 0.25$ and $\alpha = \beta = 45°$. To be more specific, it is further assumed that the unit cell size is a = b = 1 cm, the cell wall thickness $t = 0.5$ mm, and the Young's modulus for the core material $E = 100$ MPa. We apply different normal stresses in the x-direction and consider the deformations of the unit cell. Figure 5 is a plot of the applied stress versus the x-direction strain. The curve shows a linear relationship. The slope of this line gives the Young's modulus according to Eq. (4). In this case, the slope of the line yields $E_x = 92$ KPa. This core modulus is almost three orders of magnitude less than the modulus of the core material itself. The low Young's modulus of the core indicates the core is flexible. Displayed in Fig. 6 is a plot of strains in x- and y-directions. From this plot, we find the Poisson's ratio to be $\mu_{xy} = 2.03$.

The y-direction properties can be determined in a similar fashion by applying the external load in the y-direction. In this way, we can obtain an estimate of the in-plane elastic properties for a non-conventional honeycomb core with non-straight cell walls. These properties can then be used to make predictions for core deformation or core formability.

4. CONCLUSIONS

We have developed a unit cell model to generate sandwich cores with non-conventional cell shapes. In this model, the node bonds are kept straight, while other cell edges are approximated by cubic spline curves. In-plane elastic properties of non-conventional sandwich cores are evaluated using a numerical method. These core properties can be used to predict the core formability. The procedure can also be used in a reverse manner. That is, for a desired surface curvature, one can design specific cell shapes to produce a core with the desired deformation characteristics. Formable cores are useful for applications such as radar domes, and the availability of such cores will lead to reduced manufacturing costs.

ACKNOWLEDGEMENTS

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Figure 1. Sandwich cores with non-conventional cell shapes are flexible enough to be bent into complex shapes such as a sphere.

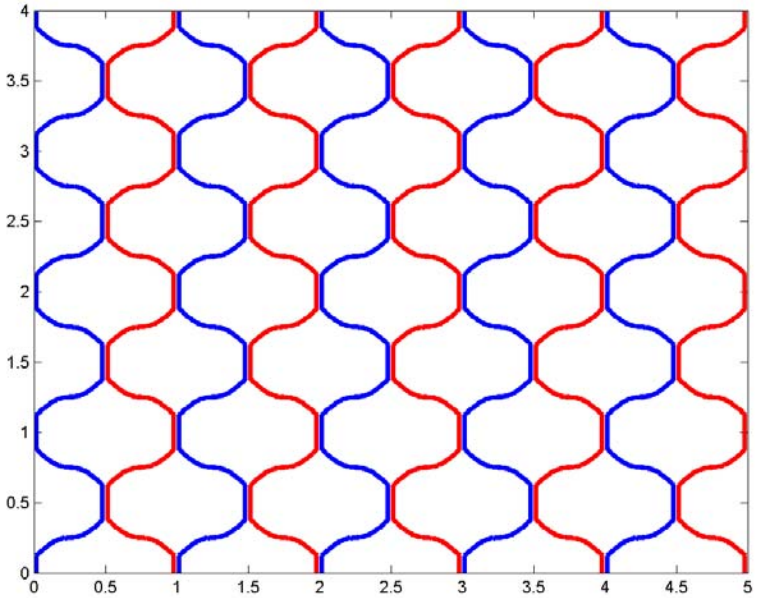

Figure 2. A non-conventional sandwich core with non-straight cell shapes. This is generated by a unit cell with h/a=0.25 and α=45°.

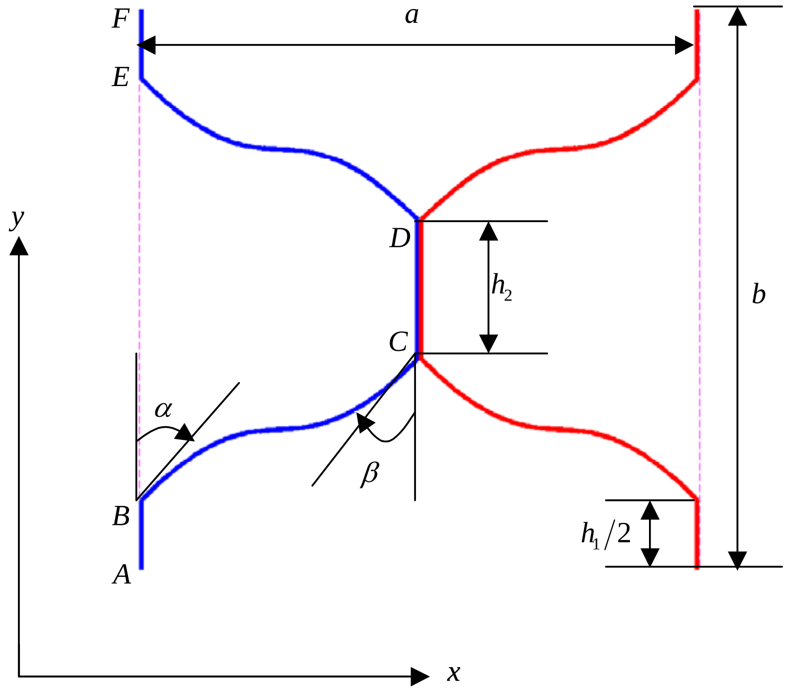

Figure 3. The unit cell for a non-conventional sandwich core.

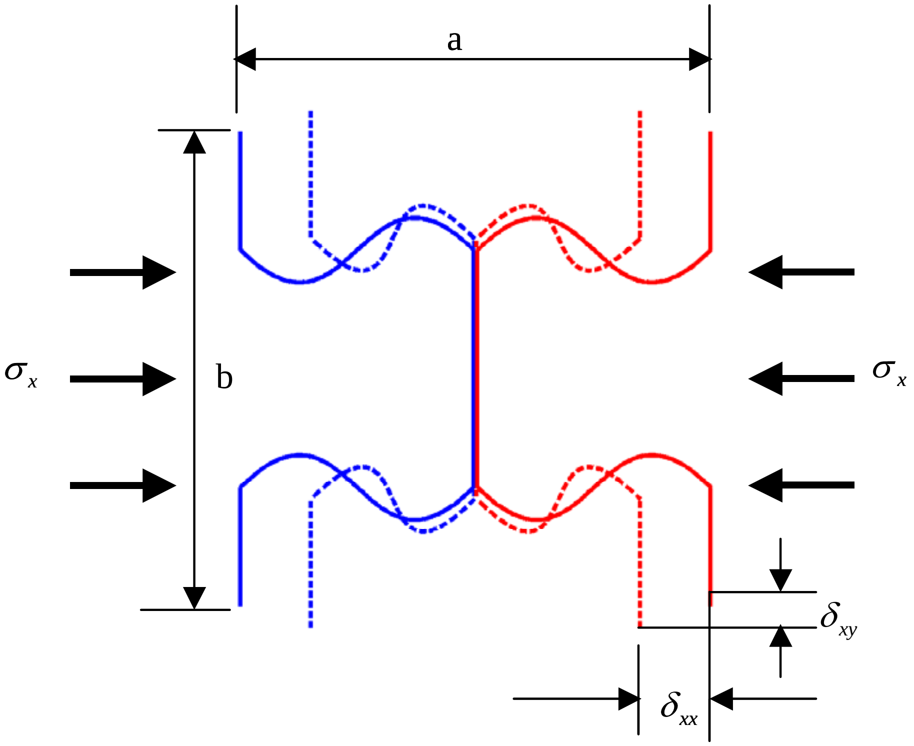

Figure 4. The unit cell is loaded in the horizontal direction to determine the in-plane elastic properties.

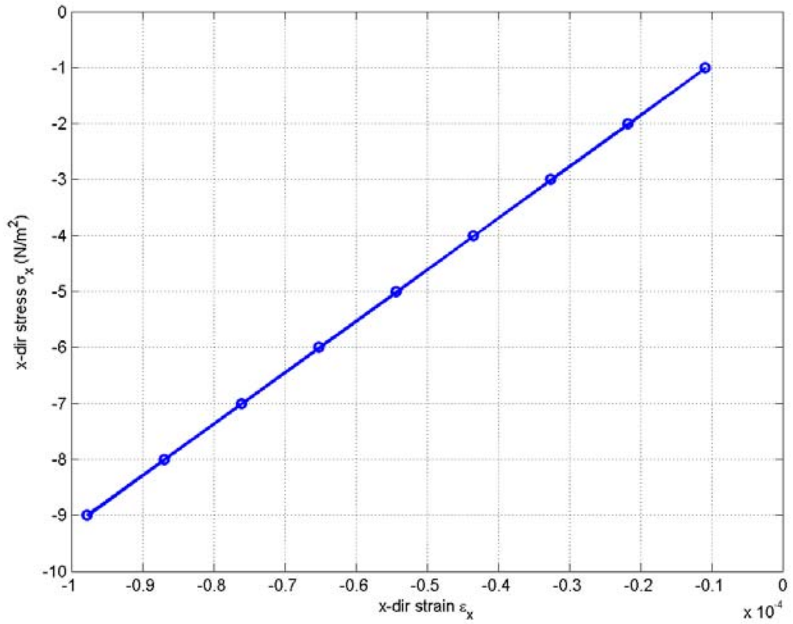

Figure 5. Plot of normal stress and strain in the case of *x*-direction loading.

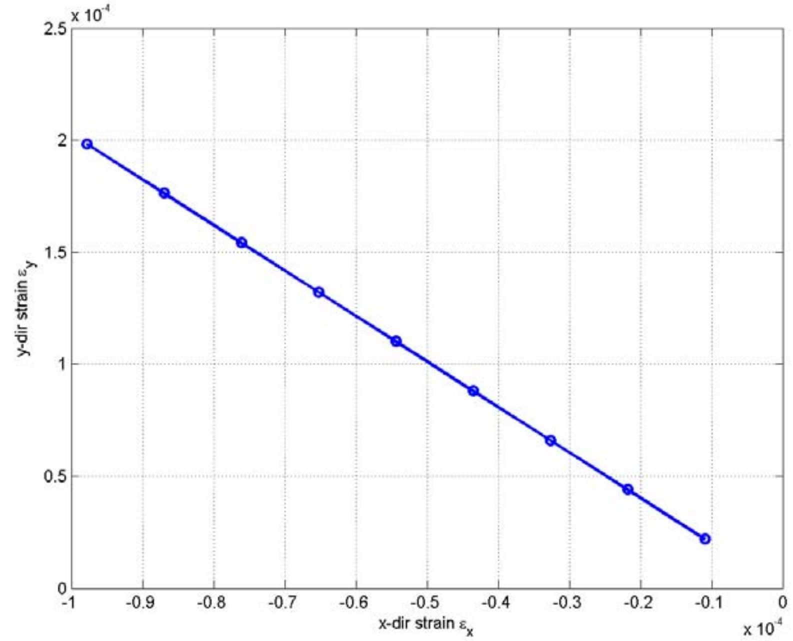

Figure 6. Plot of *x*- and *y*-strains in the case of *x*-direction loading.