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Nomex™ honeycomb core composite sandwich panels are widely used in aircraft structures. Detailed meso-scale finite element modeling of the honeycomb geometry can be used to analyze sandwich inserts, vibration response, and complex combined loading cases. The accuracy of a meso-scale honeycomb modeling technique for static load cases was evaluated. A rectangular honeycomb core was modeled with perfect hexagon honeycomb cells. Compression and shear tests simulations with linear and non-linear solutions were performed for four core densities. The simulated moduli and buckling strengths were recorded. These results were compared to property data published by honeycomb manufacturers. The simulated maximum honeycomb wall stresses at the manufacturer predicted core strengths were also recorded. The honeycomb walls' first compression deformation mode shape was observed. Sinusoidal small imperfections were then introduced in the honeycomb geometry based on that deformation mode shape. These imperfections provided a better match to manufacturer compressive modulus data while having a limited impact on the shear moduli. The simulated properties did not exactly match manufacturers' shear and compression data together for all the core densities. Modeling the honeycomb cells with rounded corners and with increased thickness at the cell junctions are potential strategies to improve the accuracy.

Keywords: sandwich panel; Nomex™ honeycomb; finite element modeling; meso-scale; imperfections

1. Introduction

Nomex™ [1] honeycomb cores are widely used in aircraft construction, for example in interior panels of commercial aircrafts, engine nacelles, control surface components, and helicopter blades. They have low density and are incorporated in light but stiff sandwich structures that can be curved or flat. Nomex™ honeycomb has good environmental resistance, fire resistance, and attractive dielectric properties. In finite element modeling of sandwich structures, the honeycomb can be modeled with its full geometry (meso-scale modeling) [2–4] or by an equivalent solid material (homogenization).[5] Under severe loading, the honeycomb is prone to local buckling. In that case, the meso-scale modeling approach is advantageous to predict the behavior of the honeycomb in details. This generally has the disadvantage of increasing the model size. Nomex™ honeycomb cores are commonly manufactured, in summary, by first adhering

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multiple strips of Nomex™ paper, expanding the papers to form hexagons, and then dipping this into phenolic resin which is subsequently cured.[6] The cores are commonly referred by their cell size and density; the honeycomb walls thickness is usually not specified. Manufacturers of Nomex™ honeycombs typically provide compressive and shear properties of the honeycomb as a bloc; the honeycomb wall's material mechanical properties are not listed. Tensile moduli were reported for Nomex™ paper (2.46–3.40 GPa) [7] and phenolic resin-coated Nomex™ paper (4.05–5.28 GPa).[8] Because of their manufacturing process, actual honeycomb core cells do not have a perfect hexagon geometry and homogeneous composition. These imperfections may include curved or pre-buckled cell walls, cell wall thickness variation, and resin accumulation at cell wall corners.[9] It has been argued that neglecting to account for imperfections in meso-scale modeling of Nomex™ honeycomb cores makes the model stiffer and stronger than reality.[10] Various methods to model these imperfections have been investigated. Varying the cell wall thickness distribution has been shown to have a great effect on the out-of-plane modulus of honeycombs.[11] As the thickness distribution at the cell corners was increased, it first caused the modulus to increase, reach a maximum, and then decrease more dramatically. Another approach is to use a model with curved or corrugated cell walls. This was investigated with finite element analysis for the in-plane properties of honeycombs.[12,13] The in-plane modulus was found to decrease exponentially with increasing cell wall curvature. With corrugated cell walls, the modulus decreased significantly with both increasing corrugation amplitude and increasing corrugation frequency. A finite element study of square wavy plates applied to cellular solids also produced similar conclusions.[14] Adding geometric imperfections to a perfect hexagonal honeycomb model can also be done by randomly moving its nodes (node-shaking), or using a small proportion of the honeycomb's first eigen mode shape as the geometry, in order to initiate cell wall buckling.[9] In the node-shaking and mode shape methods, the magnitude of the initial geometry distortion has to be set. It has been proved that the scale of the initial distortion has a great impact on the load-deformation behavior of finite element models solved by incremental steps.[14,15] This concern about imperfections, combined with limited data on the constituent material properties, makes accurately modeling a particular Nomex™ honeycomb core product in meso-scale more challenging. In this work, a Nomex™ honeycomb meso-scale finite element model using a height-wise wave-shaped initial geometry distortion will be presented. The objective is to describe the effect of initially curved honeycomb walls, focusing on out-of-plane properties, contrary to previous studies on in-plane properties (e.g. [12,13]). The intent of this text is also to present the details of the imperfections used (geometry, amplitude), as this is often not detailed in other publications dealing with simulation of experimental tests. The present study will also strictly focus on the linear portion of the honeycomb's stress/strain behavior, as we consider that this zone represents the acceptable stress level of the core in most structures. Previous studies investigated in detail the post-buckling behavior of Nomex™ honeycomb cores in out-of-plane compression (e.g. [2–4]), but we consider this outside the allowable stress level for most applications, so it is not investigated in this work. The present work will also deal with both out-of-plane compression and shear loading, while other research mainly focused on out-of-plane compression loading and energy absorption (e.g. [10]). The approach used will be inspired by using the first mode shape geometry, but aims to establish an adequate arbitrary imperfect geometry. In this way, imperfections could be pre-defined in the initial honeycomb core model. In the following, the modeling method used and the effect of the waves on the honeycomb out-of-plane normal and shear moduli will be presented. The simulated model properties will also be compared to manufacturer-published property data.

2. Modeling and analysis

A finite element model of a 3.18 mm cell size honeycomb core was built using the ANSYS V10 software (ANSYS Inc., Canonsburg, PA, USA). The rectangular model area measured 28.575 mm (9 cell height) by 31.1625 mm (11 cell rows), with a height (H) of 12.7 mm (Figure 1). These dimensions provided a reasonable number of cells (94) and a geometric symmetry center. The height corresponds to the one used in a manufacturer's tests.[16] The honeycomb cells were initially modeled straight (height wise) and perfectly hexagonal with four nodes SHELL63 shell elements. The honeycomb walls were meshed with close to square shells; the converged mesh had 6 shells width wise and 42 shells height wise (0.306 mm × 0.302 mm) (Figure 2). Two 2 mm

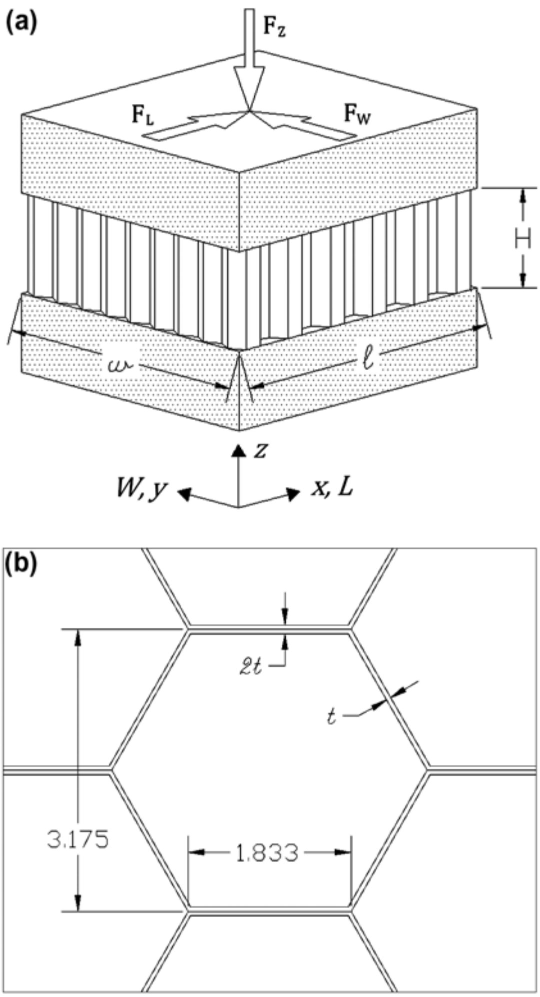

Figure 1. (a) Honeycomb core model. (b) Geometry of the honeycomb cells.

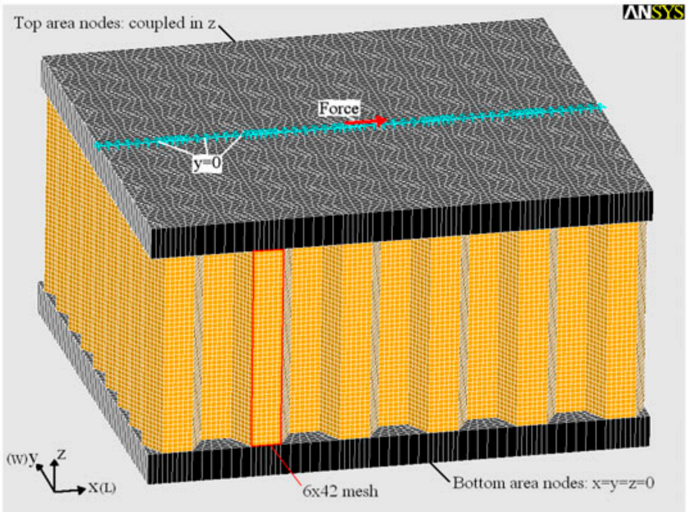

Figure 2. Honeycomb core mesh with boundary conditions.

thick steel blocks containing the core were modeled as perfectly bonded to the core. This meant that the extremities of the core cell walls had a clamped boundary condition. In typical sandwich panels, the wall extremities would be set in an epoxy adhesive. Knowing that this adhesive typically as a similar modulus as the Nomex™ core cell wall, we find the clamped condition reasonable.[2] Giglio et al. [2] considered the adhesive in their model, but found that it had a little effect on the load-displacement curve in compression. The lower face of the bottom block was restrained in *X*–*Y*–*Z*. A single compressive or shear force was applied on top of the upper block at its center; the *Z*-axis node displacements on that face were coupled equal. The *X*-axis or *Y*-axis symmetry plane top block nodes were restrained laterally for shear loads. The simulated compressive or shear stress was calculated as the applied force divided by the total rectangular core area (A_{core} = 28.575 × 31.1625 mm^2). The honeycomb material properties were based on previous correlation to bolt insert pull-out and flat-wise tension tests (Table 1); these tests involved 3.18 mm–48 kg/m^3 cores.[17] The orthotropic ratio (E_1/E_2) for these properties is 1.3, based on test results of Tsujii et al. [8]. Aminanda et al. [3] also used a similar ratio (1.31) for their numerical study, and considered the softer modulus in the out-of-plane direction, which was also adopted in the present model. This choice is based on the fabrication process of Nomex™ honeycomb core, in which we assume that the stiffer paper longitudinal milling direction ends up aligned in the in-plane direction.[10] Honeycomb cell wall isotropic properties could also be derived from analytical homogenization models, with knowledge of the core's

Table 1. Nomex™ honeycomb constituent material properties.

E_1 [MPa]	E_2 [MPa]	E_3 [MPa]	ν_{12}, ν_{23}, ν_{13}	G_{12} [MPa]	G_{23} [MPa]	G_{13} [MPa]	ρ [g/cc]
4597	3536	3250	0.212	1678	1400	1619	1.00

macroscopic properties. Considering a 3.18 mm–48 kg/m^3 core (E_z = 138 MPa (compression)) and expressions summarized in [5,18], we obtain:

$$E = \frac{E_z l(1 + \cos\Phi)\sin\Phi}{2t} = 2988\,\text{MPa}$$

with l = 1.833 mm, Φ = 60º, and t = 0.055 mm. This approach, similarly available for the shear moduli, is as far as we know limited to an isotropic cell wall material model. Staal [18] considered such an isotropic material in his Nomex$^{\text{TM}}$ honeycomb core numerical model, but obtained mixed agreement to manufacturer compression and shear moduli together. Considering this, the orthotropic values listed in Table 1 are used in the present model. Models were built for a range of common 3.18 mm cell honeycomb densities {29, 48, 64, and 80 kg/m^3}. The manufacturer-published core compressive modulus has a relative step increase from 80 to 96 kg/m^3; this could not be fully explained so higher density cores were excluded. The honeycomb wall thickness (t) was adjusted up to three decimals to closely obtain the desired densities in the model. The core buckling stress was identified using a linear block Lanczos eigenvalue solution, and also with a non-linear incremental solution with stiffness matrix updating using a Newton–Raphson solver. The manufacturer-published strength-level load was applied, or a load around 30% higher than the simulated buckling load, if the latter was found to be higher than the strength-level load. Buckling was identified by observing the evolution of nodal rotation of the honeycomb shell nodes; the non-linear buckling stress was defined as the highest applied stress before a sharp increase in nodal rotation. To observe the buckling and the honeycomb wall stress, the top and bottom three honeycomb shell elements and the peripheral partial hexagon honeycomb elements were omitted to avoid singularities. The moduli were recorded with a linear solution at 10% of the corresponding core strength load level. The moduli were calculated from the displacement (Δs) of a node at the top center of the core $\{E, G \sim (F/A_{\text{core}})/(\Delta s/H)\}$. The simulated results were compared to the average of published data from manufacturers Hexcel [16] and Plascore [19]. The various manufacturers' core strength values were assumed as the highest stress sustained by the core in their experiment (ultimate strength).

3. Results and discussion

The model was evaluated for convergence regarding mesh divisions and the number of increments for the non-linear solutions (Table 2). The model with honeycomb walls mesh divisions of 6 (width) by 42 (height) was chosen. The non-linear solutions were evaluated with 20, 30, 40, and 50 increments. Solutions with 50 increments provided a convergence within 5% of the buckling strengths obtained; we found this precision adequate for this study. Considering all load cases and densities, non-linear buckling of the core occurred after between 18 and 39 increments. Figure 3(a) shows an example of the evolution of honeycomb nodal rotation with the non-linear solution, with the buckling points selected encircled. Figure 3(b) shows nodal rotation levels for the W-direction shear case, revealing apparent diagonal local buckling of the honeycomb walls. The model's first eigenvalue buckling stress and the non-linear buckling stress were used as a comparison to manufacturers' strength data. In doing this, we initially assume that the core strength coincide with its buckling. The simulated compressive buckling stresses and modulus values are presented in Figure 4. The eigenvalue

Table 2. FEA model convergence analysis (31 kg/m^3 density core).

Wall mesh (width div. × height div.)	Compression				L-direction shear				W-direction shear			
	Modulus [MPa]	Eigen buckling [MPa]	Non-linear buckling [MPa]	$\sigma_{Z\max}$ [MPa]	Modulus [MPa]	Eigen buckling [MPa]	Non-linear buckling [MPa]	$\tau_{LZ\max}$ [MPa]	Modulus [MPa]	Eigen buckling [MPa]	Non-linear buckling [MPa]	$\tau_{WZ\max}$ [MPa]
2 × 14	110	0.158	0.125	23.3	25.6	0.0832	0.183	32.3	18.0	0.0882	0.409	23.3
4 × 28	110	0.194	0.249	23.3	25.6	0.0962	0.251	33.6	18.0	0.103	0.157	23.3
5 × 34	110	0.197	0.249	23.3	25.6	0.0974	0.228	34.2	18.0	0.104	0.144	23.3
6 × 42	110	0.199	0.249	23.3	25.7	0.0984	0.217	34.0	18.0	0.105	0.138	23.3

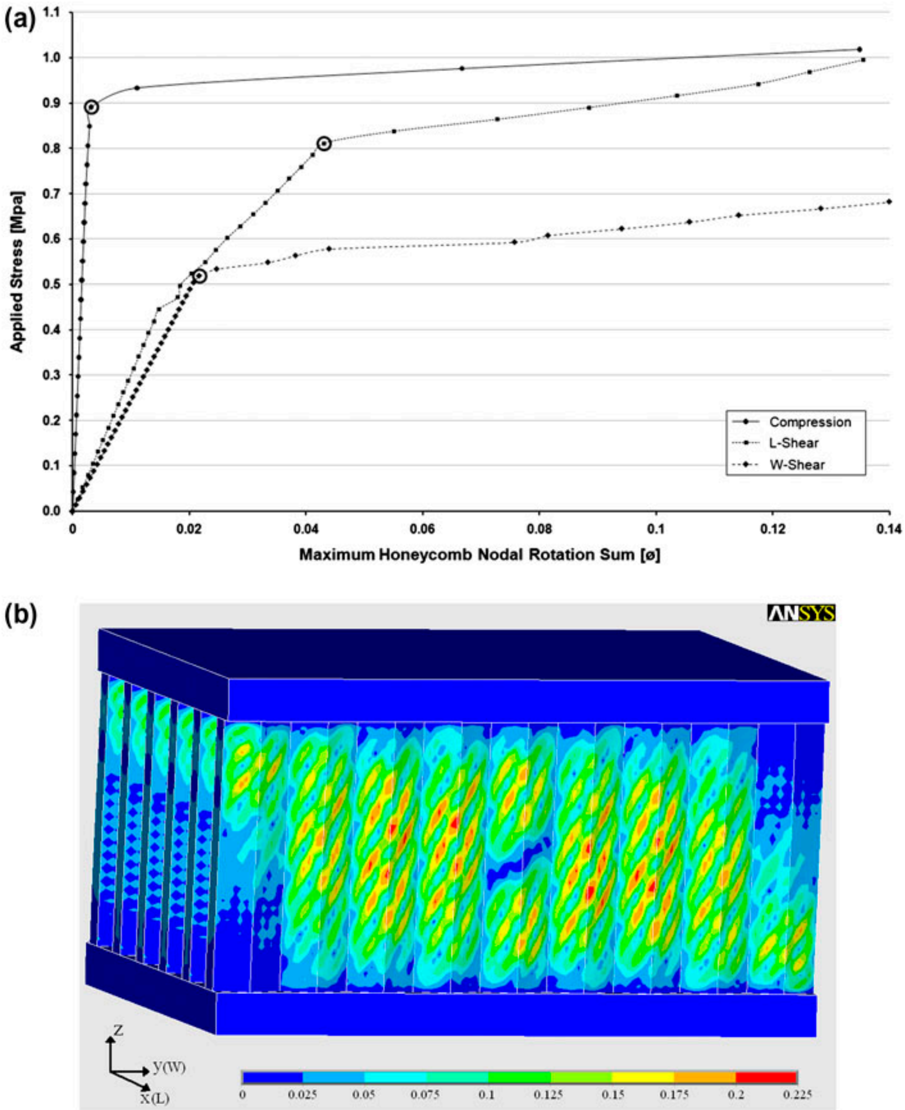

Figure 3. (a) Example of honeycomb nodal rotation evolution in the non-linear analysis (48 kg/m^3 density core). (b) Nodal rotation sum levels for the W-direction shear case (48 kg/m^3 density core at 0.68 MPa applied core stress).

buckling stress obtained is significantly lower than the manufacturers' compressive strength data. The straight hexagon model compressive modulus obtained is otherwise higher than manufacturer's data. It was previously reported in the literature that modeling the honeycomb as a perfect straight hexagon can tend to make the model appear stiffer in compression.[10] Buckling in compression first occurred on the single thickness walls on each side of the core (Figure 5(a)). The corresponding honeycomb wall mode shape profile has four sine waves (Figure 5(b)). This mode shape was used as a basis to incorporate sinusoidal waves in the honeycomb geometry. The honeycomb

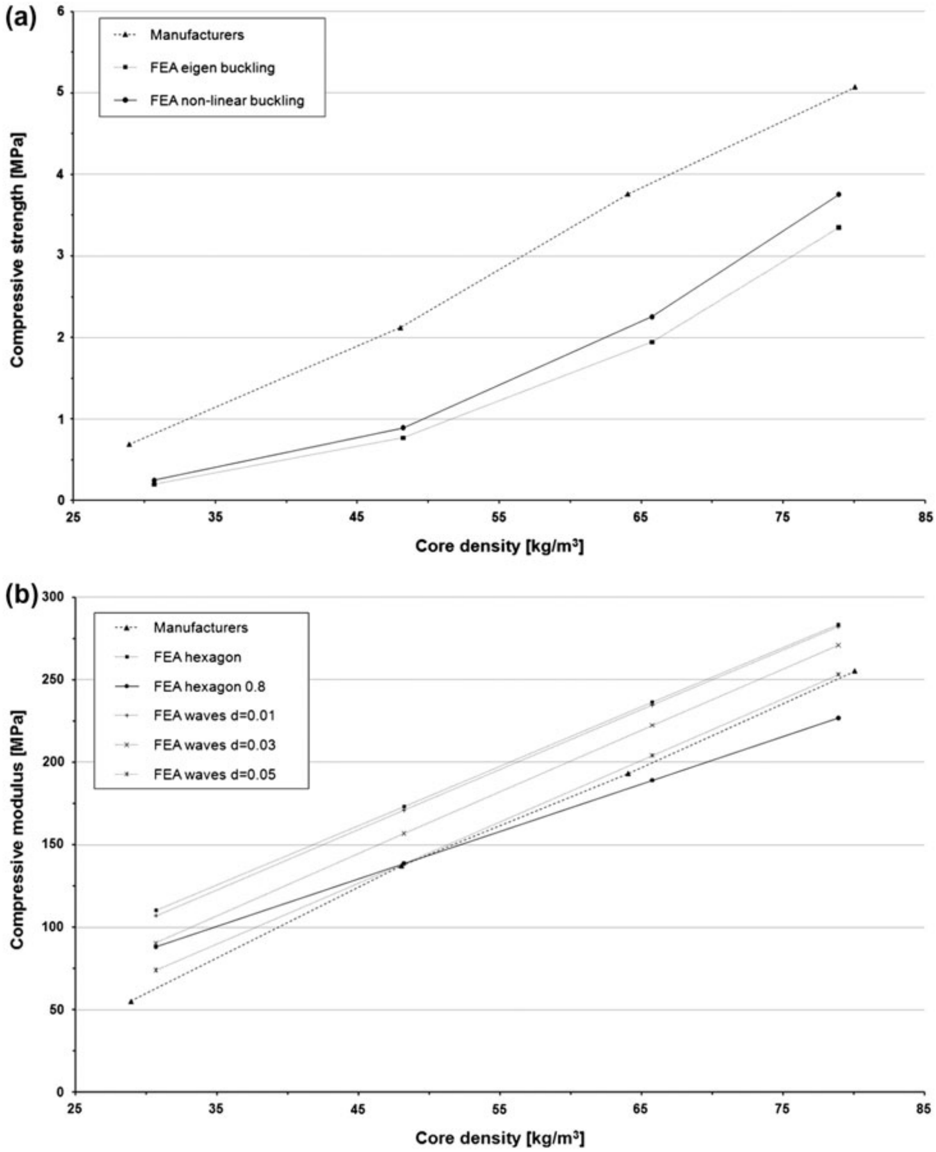

Figure 4. Compressive properties of Nomex™ honeycomb cores. (a) Strength. (b) Modulus.

nodes were moved according to $\Delta x = d{\cdot}\sin(8\pi{*}z/H)$ [mm] and $\Delta y = -d{\cdot}\sin(8\pi{*}z/H)$ [mm], where H is the core height, x, y, z are the model coordinates (Figure 1(a)), and d a parameter to control the wave amplitude. In this manner, not only the cell walls, but also the wall intersections obtain a waved geometry. Aminanda et al. [3] previously argued that these intersections are the main participants in sustaining compressive loading. The value of $d = 0.05$ was chosen to match the 48 kg/m^3 density core's compressive modulus to the manufacturers' data. This wave geometry had the effect of lowering the modulus by 30–36 MPa, closer to manufacturers' data in general. The waves would also have the exact same effect on the model's tensile modulus, which

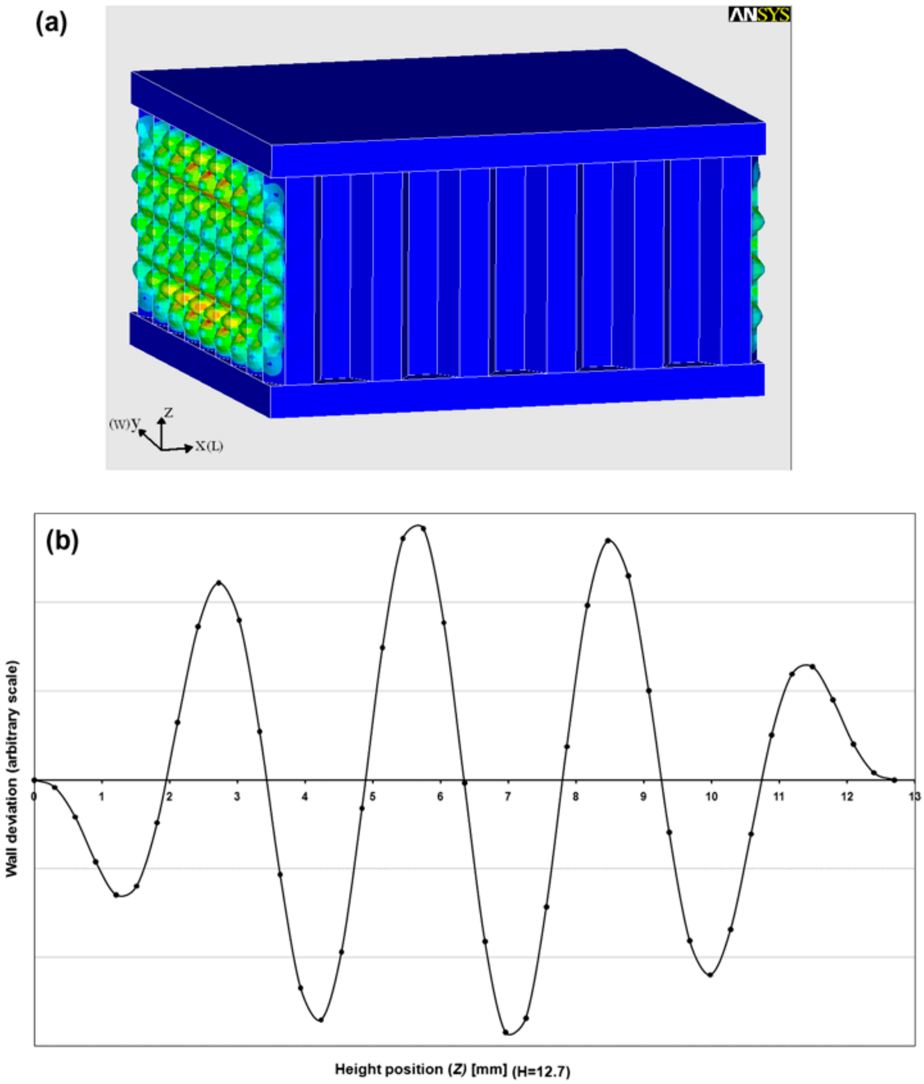

Figure 5. (a) First eigen buckling mode shape in compression. (b) Mode shape of a honeycomb wall at its center.

incidentally in simulation is identical in value to the compressive modulus. Reducing the normal and shear moduli by a factor of 0.8 also matched the 48 kg/m^3 density core's compressive modulus to the manufacturers' data; however the other density cores showed less agreement (Figure 4(b)). The simulated shear modulus increases linearly with density, as does the manufacturers' data (Figures 6 and 7). The obtained model shear modulus was both lower (L-direction) and higher (W-direction) than the manufacturers' data. The wave geometry had a small effect on the model's shear modulus values (−0.4 to −0.8 MPa). The amplitude of the waves (d value) had a nonlinear effect on the compressive modulus reduction. As an example, for the 48 kg/m^3 density core, the compressive modulus obtained was: 173.3 MPa (d = 0), 171.1 MPa (d = 0.01),

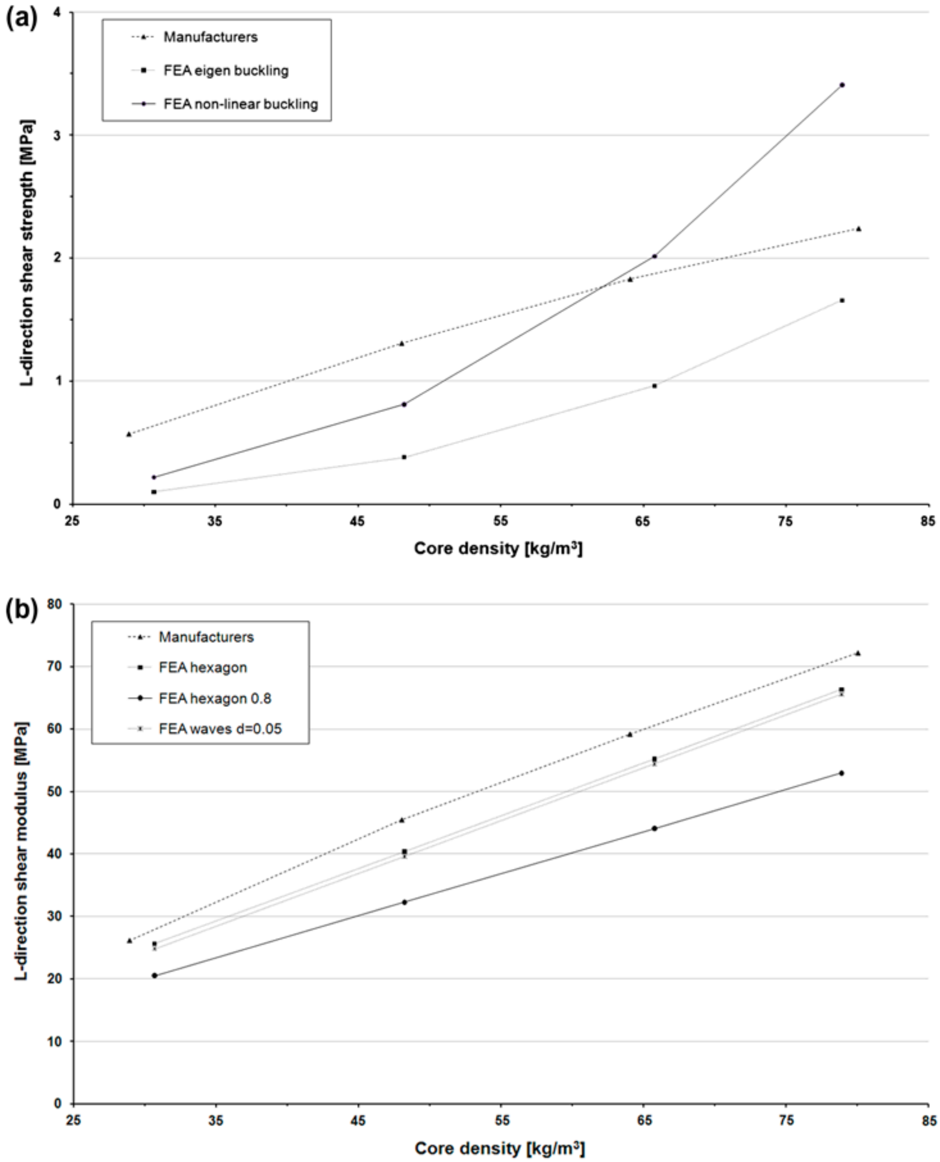

Figure 6. L-direction shear properties of Nomex^{TM} honeycomb cores. (a) Strength. (b) Modulus.

156.9 MPa (d = 0.03), and 138.5 MPa (d = 0.05). So the effect is somewhat exponential, as was previously observed for curved cell walls in the in-plane directions.[12] The maximum stress in the honeycomb walls was also recorded at the manufacturer core strength level with a linear solution (Table 3). While buckling failure is common in Nomex^{TM} cores, the maximum stress in the honeycomb walls provides additional information for analysis. Particularly, this was done to appreciate the possibility of core failure initiated by honeycomb wall ultimate strength failure, and also to compare the obtained values with Nomex^{TM} honeycomb constituent material strength

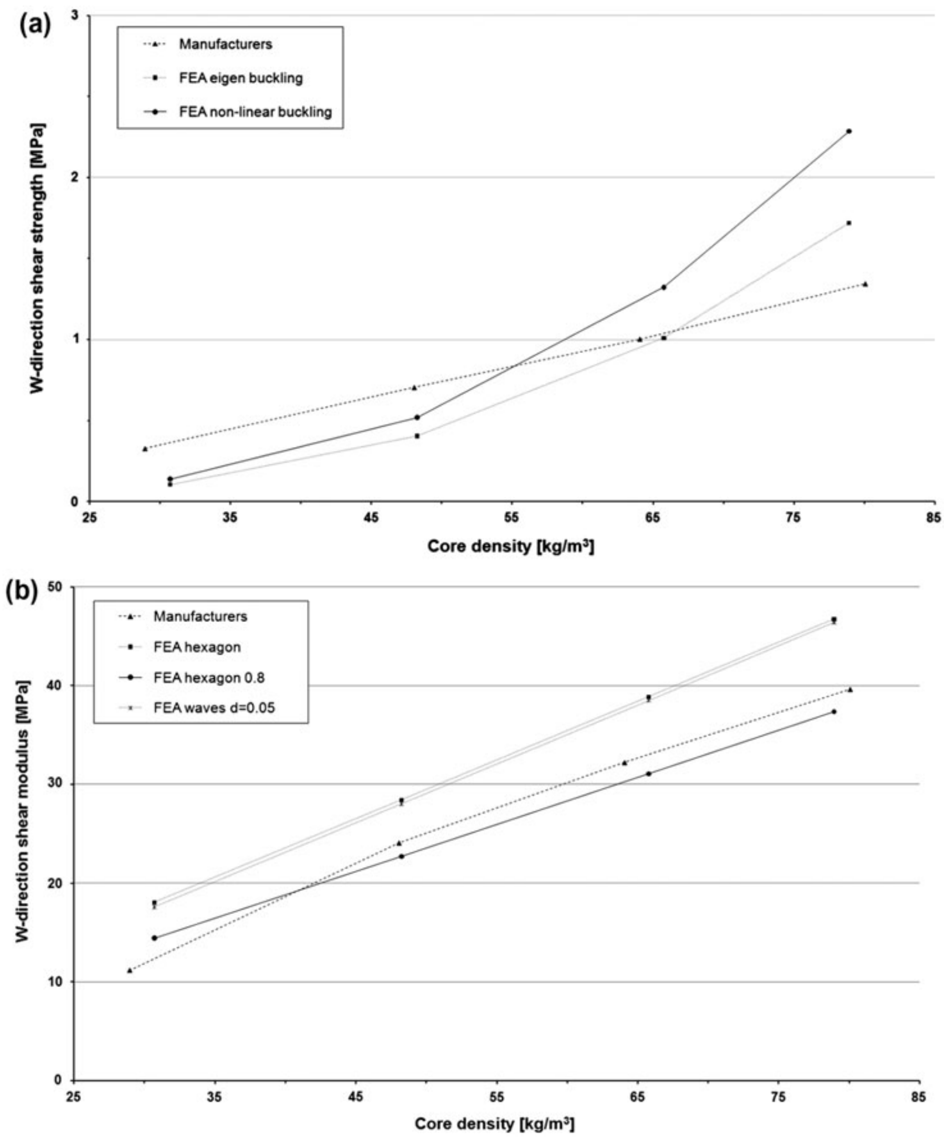

Figure 7. W-direction shear properties of Nomex™ honeycomb cores. (a) Strength. (b) Modulus.

Table 3. Honeycomb wall maximum stress at manufacturers' core strength load levels.

Model core density [kg/m^3]	31	48	66	79
Honeycomb wall thickness (t) [mm]	0.035	0.055	0.075	0.09
Linear compression: $\sigma_{Z\max}$ [MPa]	23.3	45.5	59.1	66.5
Linear L-shear: $\tau_{LZ\max}$ [MPa]	34.0	49.6	50.9	51.9
Linear W-shear: $\tau_{WZ\max}$ [MPa]	23.3	31.9	33.3	37.4
Linear compression: $\sigma_{Z\max}/t^{1.12}$ [N/m$^{3.12}$]	2.28×10^{12}	2.68×10^{12}	2.47×10^{12}	2.26×10^{12}

data. Most maximum stresses vary greatly with density; this favors buckling as the failure mode rather than honeycomb wall ultimate strength. However in the case of L-direction shear, the maximum shear stress appears to plateau in the 50–52 MPa range for the 48, 66, and 79 kg/m^3 density cores. No material shear strength data were found to compare, but this plateau may indicate that the failure in L-direction shear for these cores starts with shear stress failure of the honeycomb walls. This also would explain why the 79 kg/m^3 core's L-direction shear buckling stress found is much higher than the manufacturer's strength data; failure would be initiated by ultimate shear stress rather than shear buckling. The same 79 kg/m^3 core's simulated high W-direction shear buckling stress however cannot be explained in the same way. This discrepancy, and the otherwise low simulated compressive buckling strengths, may be attributed to modeling the honeycomb cells as perfect hexagonal. In compression, the maximum compressive stress in the honeycomb almost varies linearly with core density (from 23.3 to 66.5 MPa). Material compressive crush strength of 60 MPa was previously considered in the literature [18]; this indicates that the 79 kg/m^3 core may fail by wall ultimate compressive strength failure. In the case of tensile loading, strengths of 40.2 MPa (transverse direction) and 66.6 MPa (roll direction) were also reported from tests on phenolic resin-coated Nomex™ paper.[8] The form σ_z/t^n may be used to identify a common wall compression stress-based failure criterion. This could be used if one wants to avoid doing a buckling analysis. The exponent n = 1.12 gave the best least mean square fit to the data. In that case, the maximum $\sigma/t^{1.12}$ stress range was 2.26×10^{12}–2.68×10^{12} [N/m$^{3.12}$]. Using the lower value as the failure criteria would lead to a maximum error of 19%.

4. Conclusion

The honeycomb model built did not exactly match manufacturer's shear and compression properties together for all the core densities. The incorporation of sinusoidal waves in the honeycomb core model geometry can bring the simulated compressive modulus closer to the manufacturers' data. The amplitude of these waves can be adjusted in order to obtain a desired level of core compressive modulus reduction, and this relation is nonlinear. The shear moduli are only slightly affected by the waves. Over the range of core densities evaluated, these waves performed better than merely scaling the honeycomb material's moduli in order to match a single core's compressive modulus. At the manufacturer's predicted core maximum stress levels, the honeycomb wall maximum shear stress levels were in the range 23–52 MPa, depending on core density and load direction. In the case of L-direction shear, this stress plateaus around 50–52 MPa for the 48, 66, and 79 kg/m^3 density cores, indicating a possible shear stress failure mode. Likewise in compression, the 79 kg/m^3 density core had a maximum wall stress of 66.5 MPa, which when compared to material strength data, may indicate a compressive stress failure mode. Some further modifications to the hexagon geometry, like using rounded (filleted) cell corners and/or increasing the wall thickness distribution at the cell junctions, along with material property identification, are possible avenues to improve the model's accuracy.

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