Flatwise Testing Modeling Study On Aluminium Honeycomb Panel

Sri Ramayanti[1]

[1]Research Center for Satellite Technology, BRIN, Indonesia

e-mail: sri.ramayanti@brin.go.id

Received: 20-11-2022. Accepted: 11-01-2023. Published: 31-01-2023
DOI: 10.30536/j.jtd.2022.v20.a3935

Abstract

Honeycomb sandwich structures are widely used in space applications due to their exceptional performance. Extensive research has been conducted on the response of honeycomb structures to various external loads. The out-of-plane strength, including compression and tensile properties, is a critical aspect of honeycomb structures. Despite some experimental and numerical studies, research specifically addressing the tensile direction, such as flatwise tensile testing in honeycombs, remains limited. This testing focuses on the bond strength between the face sheets and the honeycomb core, as well as the tensile strength of the core itself. Utilizing finite element analysis (FEA) has proven effective for characterizing honeycomb structures under various load conditions. However, the complex geometry of the core requires an enormous number of elements, increasing computation times. Thus, simplifying the model by replacing the hexagonal geometry with a homogenized solid layer with effective material properties is necessary. This study focuses on flatwise tensile testing of aluminum honeycomb using different modeling approaches: discrete, continuum, and equivalent plate models. The discrete model serves as the reference due to its detailed structural representation. The continuum-Gibson model, while reasonably accurate in stress estimation, tends to overestimate displacement. Both equivalent models, Hoff and Reissner, significantly overestimate displacement, with Hoff underestimating stress and Reissner overestimating it. In contrast, equivalent models offer insights, but their accuracy varies, necessitating further calibration for precise predictions. Future research should validate these simulation results with real tests.

Keywords*: Honeycomb structures, flatwise tensile testing, Finite Element Analysis (FEA).*

Nomenclature (Optional)

E_i	=	Effective Young Modulus parallel to X_i direction, i=1, 2,3
E_c	=	Young Modulus of cell wall, Pa
d	=	Cell size, m
L	=	Length of the inclined cell wall, m
h	=	Length of the vertical cell wall, m
t	=	Thickness of the wall, m
θ	=	Angle, degree
ρ^*	=	Effective density of the honeycomb
ρ_c	=	Mass density of the solid cell wall material
ρ_f	=	Mass density of the face material
v_{ij}	=	Effective Poisson's ratio of the honeycomb core I the material system of coordinates
v_c	=	Poisson's ratio of the solid cell wall

G_{ij}	=	Effective Shear Modulus of the honeycomb core I the material system of coordinates
G_c	=	Shear modulus of the solid cell wall material
v_{eq}	=	Equivalent Poisson's ration
v_f	=	Poisson's ratio of the face
t_{eq}	=	Equivalent thickness
h_c	=	Core thickness
h_f	=	Face thickness
E_{eq}	=	Equivalent young modulus
G_{xeq}	=	Equivalent shear modulus in x direction
G_{cxz}	=	Out-of-plane shear modulus in xz plane
G_{yeq}	=	Equivalent shear modulus in y direction
G_{cyz}	=	Out-of-plane shear modulus in yz plane
ρ_{eq}	=	Equivalent mass density

1. Introduction

Honeycomb sandwich structures are commonly used in space applications due to their high stiffness-to-weight and high strength-to-weight ratio[1]. They can be used as the main structure, structural support, and also in solar arrays [2][3][4]. Usually sandwich structure consist of two facing layers of thin sheets separated by a core material [5]. The thin sheets consist of high stiffness material commonly made of aluminum or composite material to support in-plane loads and the core uses light material such as aluminum honeycomb to sustain the strong faces [6].

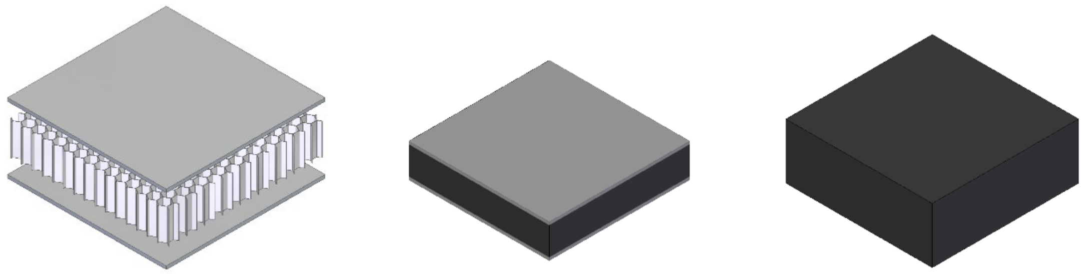
Significant attention has been dedicated to studying how honeycomb structures respond to various external loads. This includes in-plane axial and shear loads, biaxial loading, out-of-plane transverse shear, bending, and more complex load combinations [7]. The out-of-plane strength such as compression and tensile is a critical aspect of honeycomb structures. Although a few experimental and numerical studies have been conducted, research specifically addressing the tensile direction such as flatwise tensile testing in honeycombs remains limited. Flatwise tensile testing of honeycomb structures is important for understanding and evaluating the performance of sandwich panels under tensile loads applied perpendicular to their faces. This testing focuses on the bond strength between the face sheets and the honeycomb core, as well as the tensile strength of the core itself [8]. Djarot et al. studied experimental flatwise tensile on carbon fiber-reinforced plastic and focused on the preparation of core using methyl-ethyl-ketone[9]. Roy et al. compared the experimental and analytical of the Nomex honeycomb using discrete modeling in finite element analysis (FEA) [10]. Utilizing FEA has proven effective for characterizing honeycomb structures under various load conditions. However, due to the complex geometry of the core, it will need an enormous number of elements that make calculation times increase. Hence, it is required to simplify the model by replacing the hexagonal geometry with to homogenized solid layer with effective material properties [11][12], [13]. Therefore, this present study will focus on flatwise tensile testing on aluminum honeycomb by using different modeling techniques approach, discrete, continuum modeling, and equivalent plate models as can be seen in Figure 2-1.

2. Methodology

A finite element model of a honeycomb panel with the flat-wise tension test was developed to compare various modeling approaches such as discrete, continuum, and equivalent plates, utilizing SIMCenter software for the analysis. The honeycomb panel employed in this modeling comprised an aluminum 7075 series for the face sheets and an aluminum 5056 type for the core. The material properties for both the face sheets and the core are detailed in Table 2-1

Table 2-1: Geometry And Materials Parameters Of Honeycomb Panel

Position	**Geometric parameters (m)**	**Materials parameters**
Core layer (Al 5056)	$h_c = 1 \times 10^{-2} m$ $t = 6.67 \times 10^{-5} m$ $\mathrm{D} = 0.032 m$	$E = 71.0\ GPa$ $G = 25.9\ GPa$ $\mu = 0.33$ $\rho = 2640\ kg/m^3$
Aluminum face (Al 7075)	$h_f = 1 \times 10^{-3} m$	$E = 71.7\ GPa$ $G = 26.9\ GPa$ $\mu = 0.33$ $\rho = 2810\ kg/m^3$



(a) (b) (c)

Figure 2-1: Honeycomb panel models for FEA (a) discrete model, (b) continuum model, (c) equivalent plate

2.1. Discrete modeling

In this modeling, the honeycomb panel uses the intricate cellular details of the core, enabling a more detailed analysis. However, because of the complexity and large number of cells in a full-scale honeycomb shell structure, this approach is less favored due to the extensive computational time required. Nevertheless, this modeling approach will serve as a reference for comparison with continuum and equivalent plate modeling. The details of the honeycomb structure can be seen in Figure 2-2.

2.2. Continuum modeling

In this modeling, the core of the honeycomb structure will be represented using orthotropic material properties. The Gibson model, the most widely adopted analytical framework for determining effective material properties, assumes that the deformation of the honeycomb walls is primarily due to the bending of the inclined walls. This model provides a set of analytical formulas applicable to both classical and commercial honeycombs. Classical honeycombs have walls of uniform thickness, whereas commercial honeycombs feature double walls attached by gluing along the ribbon direction. In this study, we use commercial honeycombs whose properties can be seen in Table 2-1.

The effective modulus is given as follows[14]:

$$E_1 = \frac{E_c \left(\frac{t}{L}\right)^3 cos(\theta)}{\left(\frac{h}{L} + sin(\theta)\right) sin^2(\theta)} \tag{2-1}$$

$$E_2 = \frac{E_c\left(\frac{t}{L}\right)^3\left(\frac{h}{L} + sin(\theta)\right)}{cos^3(\theta)} \quad (2\text{-}2)$$

$$v_{12} = \frac{cos^2(\theta)}{\left(\frac{h}{L} + sin(\theta)\right)sin(\theta)} \quad (2\text{-}3)$$

$$G_{12} = E_c\left(\frac{t}{L}\right)^3 \frac{1 + sin(\theta)}{3cos(\theta)} \quad (2\text{-}4)$$

$$E_3 = \frac{\rho}{\rho_c} E_c \quad (2\text{-}5)$$

$$v_{13} = \frac{E_1}{E_3} v_c \quad (2\text{-}6)$$

$$v_{23} = \frac{E_2}{E_3} v_c \quad (2\text{-}7)$$

$$G_{13} = G_{23} = G_c\left(\frac{t}{L}\right)\frac{cos(\theta)}{\left(\frac{h}{L} + sin(\theta)\right)} \quad (2\text{-}8)$$

$$\rho^* = \rho_c \frac{\frac{t}{L}\left(\frac{h}{L} + 1\right)}{cos\theta\left(\frac{h}{L} + sin\theta\right)} \quad (2\text{-}9)$$

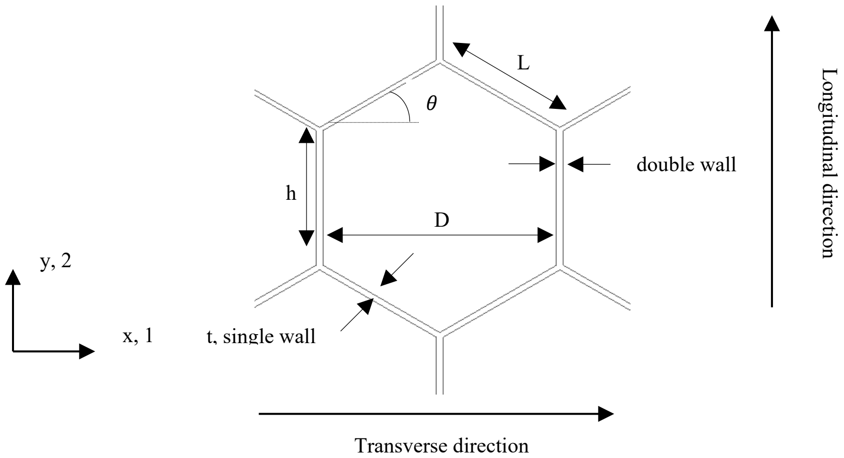


Figure 2-2: Details of 2D hexagonal honeycomb cell

2.3. Equivalent Model

In this modeling, the honeycomb panel including the core and face will be converted into an equivalent isotropic plate by equalizing the bending stiffness between the honeycomb sandwich plate and the equivalent plate [15].

2.3.1. Reissner Theory

According to Reissner's theory, the surface panel is considered very thin with a uniformly distributed stress along its thickness, resulting in a state of membrane stress. Given the soft nature of the sandwich core, the stress distribution parallel to the XY plane is disregarded. This assumption indicates that the tensile stresses in the x and y directions are equal, while the shear stress in the xy direction is zero within the sandwich. Furthermore, the stress component in the honeycomb structure is assumed to be minimal, leading to the assumption that both tensile stress and strain in the z direction are zero.

The equivalent parameter of Reissner's theory can be seen as follows:

$$v_{eq} = v_f \tag{2-10}$$

$$t_{eq} = \sqrt{3}\left(h_c + h_f\right) \tag{2-11}$$

$$E_{eq} = \frac{2E_f h_f}{\sqrt{3}\left(h_c + h_f\right)} \tag{2-12}$$

$$G_{xeq} = \frac{3}{\sqrt{3}} G_{cxz}\, or\, G_{yeq} = \frac{3}{\sqrt{3}} G_{cyz} \tag{2-13}$$

$$\rho_{eq} = \frac{2\rho_f h_f + \rho_c (H - 2h_f)}{t_{eq}} \tag{2-14}$$

2.3.2. Hoff Theory

This theory extends classical plate theory to account for nonlinear behavior and large deformations, which are significant in many practical applications of sandwich panels. Compared with the Reisner theory, Hoff theory is more complex considering the bending stiffness of the panel. Therefore, there will be some modification in the equivalent parameter, as can be seen as follows:

$$v_{eq} = v_f \tag{2-15}$$

$$t_{eq} = \sqrt{h_f^2 + 3\left(h_c + h_f\right)^2} \tag{2-16}$$

$$E_{eq} = \frac{2E_f h_f}{\sqrt{h_f^2 + 3\left(h_c + h_f\right)^2}} \tag{2-17}$$

$$G_{xeq} == \frac{\left(h_c + h_f\right)^2}{hc\sqrt{h_f^2 + 3\left(h_c + h_f\right)^2}} G_{cxz} \tag{2-18}$$

$$G_{yeq} == \frac{\left(h_c + h_f\right)^2}{hc\sqrt{h_f^2 + 3\left(h_c + h_f\right)^2}} G_{cyz} \tag{2-19}$$

$$\rho_{eq} = \frac{2\rho_f h_f + \rho_c h_f}{\sqrt{h_f^2 + 3\left(h_c + h_f\right)^2}} \tag{2-20}$$

A 50x50 mm panel will be consistently utilized across all modeling approaches based on ASTM C297. In discrete modeling, only the core and face sheets will be included. The continuum method will feature a single core replaced by an orthotropic layer, while the equivalent model will employ a single plane with an equivalent thickness determined by Equations (2-11) and (2-16).

The top and bottom faces of the sandwich panel were connected to steel block models of the same dimensions as the panel. The adhesive between the face-core block was neglected in this simulation, and the connection was modeled as perfectly bonded, ensuring no sliding between components. The outermost parts of the blocks were restrained in the X, Y, and Z directions to prevent any translation and rotation, facilitating easy measurement of the reaction forces. A load of 100 kN was applied in both the -Z and

+Z directions on the blocks, replicating the load that will be used in future testing with a Universal Testing Machine (UTM).

The analytical results from Equations (2-1) to (2-20) were employed in this simulation, as detailed in Table 2-2.

Table 2.2: Result Parameters Of The Continuum And Equivalent Theories

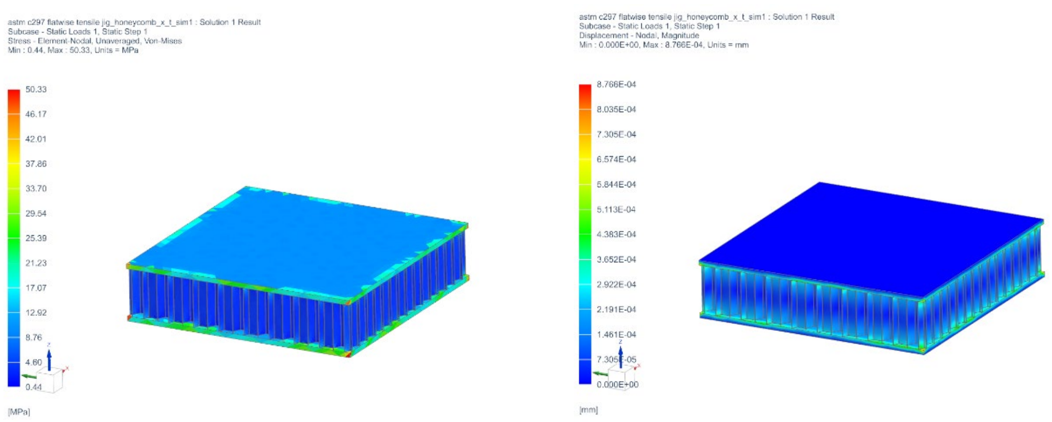
Elastic parameters	**Continuum modeling**	**Reissner Theory**	**Hoff Theory**
Thickness	-	0.019 m	0.019m
Elastic modulus	$E_1 = 7.79 \times 10^6 Pa$ $E_2 = 7.79 \times 10^6 Pa$ $E_3 = 1.46 \times 10^{12} Pa$	$E_{eq} = 7.53 \times 10^9 Pa$	$E_{eq} = 7.52 \times 10^9 Pa$
Shear Modulus	$G_{12} = 1.95 \times 10^6 Pa$ $G_{13} = 5.61 \times 10^8 Pa$ $G_{23} = 5.61 \times 10^8 Pa$	$G_{xeq} = 4.66 \times 10^{10} Pa$ $G_{yeq} = 4.66 \times 10^{10} Pa$	$G_{xeq} = 2.95 \times 10^{10} Pa$ $G_{yeq} = 4.66 \times 10^{10} Pa$
Poisson's ratio	$v_{12} = 0.6$ $v_{13} = 1.77 \times 10^{-6}$ $v_{23} = 1.77 \times 10^{-6}$	-	-
Density	$\rho = 99.6\ kg/m^3$	$\rho_{eq} = 72.59\ kg/m^3$	$\rho_{eq} = 72.49\ kg/m^3$

3. Result and Analysis

Figure 3-1 presents the results of the FEA flatwise tension test using discrete modeling. It is evident that the greatest stress occurs at the ends and outer sides of the honeycomb, affecting both the core and the aluminum face. The largest displacement, however, is observed only at the top and bottom of the honeycomb core, with no significant displacement in the aluminum face. This indicates that, under a tensile force with a free out-of-plane boundary, damage is confined to the core. This outcome aligns with expectations, as acceptable damage in real testing scenarios is typically limited to the core [8].

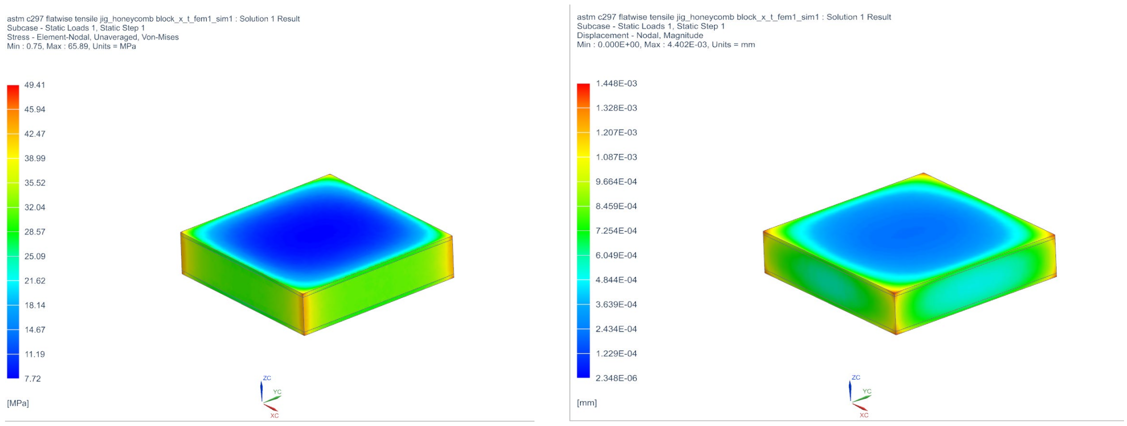
Figure 3-2 displays the results of the FEA flatwise tension test using continuum modeling. The stress distribution closely resembles that of the discrete modeling results, with stress occurring on the outer sides of the honeycomb panel. The displacement simulation results are also similar.

Figures 3-4 and 3-5 show the FEA results for the honeycomb equivalent plate according to Hoff's theory and Reissner's theory, respectively. Both models exhibit similar stress and displacement patterns. However, the location of the maximum stress points differs significantly from the FEA results obtained from the discrete and continuum honeycomb models.



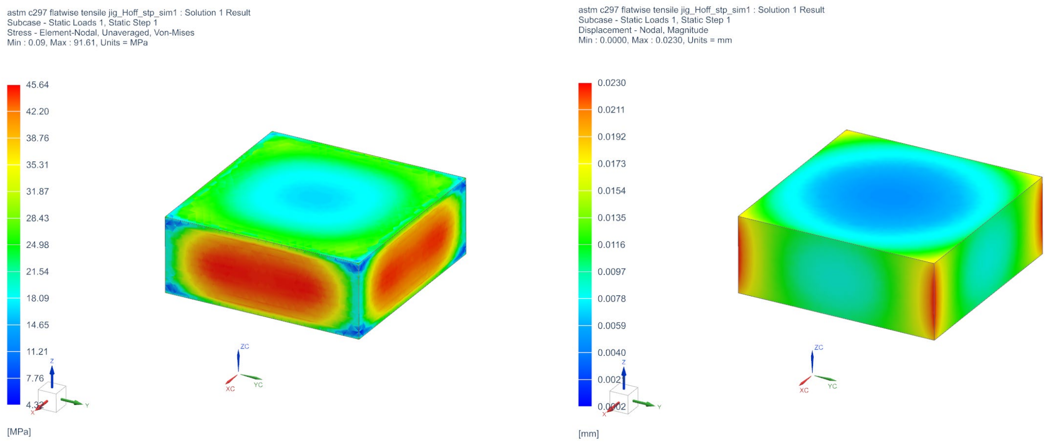
(a) (b)

Figure 3-1: FEA of the flatwise tension test of discrete modeling (a) Stress, (b) Displacement



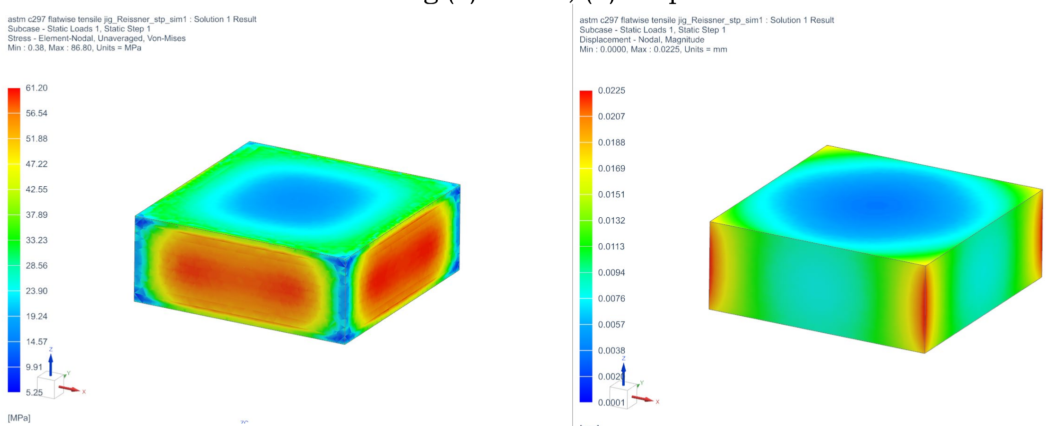
(a) (b)

Figure 3-2: FEA of the flatwise tension test of Continuum modeling (a) Stress, (b) Displacement



(a) (b)

Figure 3-4: FEA of the flatwise tension test of Equivalent plate-Hoff Theories modeling (a) Stress, (b) Displacement



(a) (b)

Figure 3-5: FEA of the flatwise tension test of Equivalent plate-Reissner Theories modeling (a) Stress, (b) Displacement

Table 3-1 shows the result of the FEA flatwise tension test of all three models. The discrete model serves as the reference for comparison which shows a displacement of 0.00087 mm and a stress of 50.33 MPa.

The continuum-Gibson model results in a displacement of 0.001448 mm, which is approximately higher than the discrete model. The stress value of 49.61 MPa is slightly lower than the discrete model, with a difference of about 1.4%. This value provides a reasonable approximation. The equivalent-Hoff model shows a significantly larger displacement of 0.023 mm, which is substantially higher than the discrete model. This indicates that the equivalent-Hoff model may not accurately capture the stiffness of the honeycomb structure. The stress value of 45.64 MPa is lower than the discrete model by about 9.3%, suggesting an underestimation of the material's strength. The equivalent-Reissner model yields a displacement of 0.0225 mm, which is also considerably higher than the discrete model. The stress value of 61.2 MPa, however, is significantly higher than the discrete model by 21.6%. This suggests that the Reissner model may overestimate the stress in the material under similar loading conditions.

Table 3-1: Simulation Result Of All Three Model Approaches

Type	Discrete	Continuum-Gibson Model	Equivalent-Hoff Model	Equivalent-Reissner Model
Displacement (mm)	0.00087	0.001448	0.023	0.0225
Stress (MPa)	50.33	49.61	45.64	61.2

4. Conclusions

In the present study, various modeling for FEA analysis in honeycomb structure's response to flatwise tensile testing such as discrete, continuum, and equivalent plate modeling are reviewed. The discrete model is used as the reference due to the use of the details of the structure. The continuum-Gibson model, while reasonably accurate in stress estimation, tends to overestimate displacement. Both equivalent models, Hoff and Reissner, significantly overestimate displacement, with Hoff underestimating stress and Reissner overestimating it. Therefore, while equivalent models can provide insights, their accuracy varies, and they may not be suitable for precise predictions without further calibration. Future research should validate these simulation results with real tests.

References

S. D. Pan, L. Z. Wu, Y. G. Sun, Z. G. Zhou, and J. L. Qu, "Longitudinal shear strength and failure process of honeycomb cores," *Compos Struct*, vol. 72, no. 1, pp. 42–46, Jan. 2006, doi: 10.1016/j.compstruct.2004.10.011.

J. R. Tanzman, "Material considerations in the STEREO solar array design," *Acta Astronaut*, vol. 63, no. 11–12, pp. 1239–1245, Dec. 2008, doi: 10.1016/j.actaastro.2008.06.027.

S. Ramayanti, P. A. Budiantoro, A. Fauzi, E. Fitrianingsih, and E. N. Nasser, "Comparative Study of Deployable Satellite Solar Panel Structure between Carbon Fiber Reinforced Polymer and Al-7075 Honeycomb," in *2022 IEEE International Conference on Aerospace Electronics and Remote Sensing Technology, ICARES 2022 - Proceedings*, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/ICARES56907.2022.9993517.

[B. J. Kim and D. G. Lee, "Development of a satellite structure with the sandwich T-joint," *Compos Struct*, vol. 92, no. 2, pp. 460–468, Jan. 2010, doi: 10.1016/j.compstruct.2009.08.030.

L. Teng, X. D. Zheng, and Z. H. Jin, "Performance optimization and verification of a new type of solar panel for microsatellites," *International Journal of Aerospace Engineering*, vol. 2019, 2019, doi: 10.1155/2019/2846491.

K. Il Song, J. Y. Choi, J. H. Kweon, J. H. Choi, and K. S. Kim, "An experimental study of the insert joint strength of composite sandwich structures," *Compos Struct*, vol. 86, no. 1–3, pp. 107–113, Nov. 2008, doi: 10.1016/j.compstruct.2008.03.027.

S. Sorohan, D. M. Constantinescu, M. Sandu, and A. G. Sandu, "On the homogenization of hexagonal honeycombs under axial and shear loading. Part I: Analytical formulation for free skin effect," *Mechanics of Materials*, vol. 119, pp. 74–91, Apr. 2018, doi: 10.1016/j.mechmat.2017.09.003.

ASTM International, "Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions-ASTM C297," 2004 [Online]. Available: www.astm.org,

D. Widagdo, A. Kuswoyo, T. O. Nurpratama, and B. K. Hadi, "Experimental flatwise tensile strength dataset of carbon fibre reinforced plastic sandwich panels with different core material preparations," *Data Brief*, vol. 28, Feb. 2020, doi: 10.1016/j.dib.2019.105055.

R. Roy, K. H. Nguyen, Y. B. Park, J. H. Kweon, and J. H. Choi, "Testing and modeling of Nomex™ honeycomb sandwich Panels with bolt insert," *Compos B Eng*, vol. 56, pp. 762–769, 2014, doi: 10.1016/j.compositesb.2013.09.006.

S. Sorohan, D. M. Constantinescu, M. Sandu, and A. G. Sandu, "In-plane homogenization of commercial hexagonal honeycombs considering the cell wall curvature and adhesive layer influence," *Int J Solids Struct*, vol. 156–157, pp. 87–106, Jan. 2019, doi: 10.1016/j.ijsolstr.2018.08.007.

J. Yuan, L. Zhang, and Z. Huo, "An Equivalent Modeling Method for Honeycomb Sandwich Structure Based on Orthogonal Anisotropic Solid Element," *International Journal of Aeronautical and Space Sciences*, vol. 21, no. 4, pp. 957–969, Dec. 2020, doi: 10.1007/s42405-020-00259-6.

N. Ahmed, N. Zafar, and H. Z. Janjua, "Homogenization of Honeycomb Core in Sandwich Structures: A Review," *Proceedings of 2019 16th International Bhurban Conference on Applied Sciences & Technology*, pp. 159–173, Jan. 2019.

L. J. Gibson, M. F. Ashby, and G. S. Schajer, "The Mechanics of two-dimensional cellular materials," *Proc R Soc Lond A Math Phys Sci*, vol. A 382, pp. 25–42, 1982.

W. Wang *et al.*, "Comparative application analysis and test verification on equivalent modeling theories of honeycomb sandwich panels for satellite solar arrays," *Advanced Composites Letters*, vol. 29. SAGE Publications Ltd, 2020. doi: 10.1177/0963693520963127.