www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVE OF MECHANICAL ENGINEERING

DOI: 10.24425/ame.2025.156869 2025, Vol. 72, No. 4, pp. 627–645

Fatemeh ASADI TALEBBEIGI [1], Saeed JAMEI [2], Mohammad Amin ESABAT [2]

Enhanced pressure tolerance and deformation reduction in orthotropic honeycomb sandwich panels under fluid-structure interaction

Received 23 May 2025, **Revised** 26 July 2025, **Accepted** 21 October 2025, **Published online** 28 November 2025

Keywords: fluid-structure interaction, honeycomb composite, orthotropic materials, pressure tolerance, structural efficiency

Lightweight sandwich structures with honeycomb cores represent a critical advancement in engineering design, offering superior strength-to-weight ratios crucial for aerospace, marine, and civil applications. While extensive research exists on flows past isotropic rectangular cylinders, the fluid-structure interaction (FSI) behavior of orthotropic honeycomb structures remains poorly understood. This study investigates how the orthotropic characteristics of honeycomb sandwich panels affect their structural responses under fluid loading conditions. Using ANSYS CFX, we conducted three-dimensional finite volume simulations with one-way FSI coupling at Reynolds numbers ranging from 5×10^4 to 2.5×10^5. The computational domain was validated through mesh convergence studies and compared against existing experimental data for rectangular cylinders. Two cases were analyzed: honeycomb sandwich panels and equivalent-weight flat panels, both subjected to identical flow conditions. Results demonstrate that honeycomb panels exhibit superior performance, tolerating 17% higher pressure loads while showing 28% less deformation compared to flat panels. This enhanced structural efficiency is attributed to the honeycomb core's ability to distribute loads more effectively through its cellular structure. Our findings provide quantitative guidance for designing honeycomb sandwich panels in fluid-loaded applications, particularly in marine and aerospace environments where structural efficiency is paramount.

✉ Saeed JAMEI, email: jameisa@.pgu.ac.ir

[1] Ocean Engineering Department, Texas A&M University, Galveston, USA

[2] Department of Marine Engineering, Faculty of Engineering, Persian Gulf University, Bushehr, Iran

1. Introduction

The design and optimization of lightweight structures capable of withstanding complex fluid-structure interactions (FSI) represents one of the most challenging frontiers in modern engineering. This challenge is particularly acute in marine, aerospace, and civil engineering applications, where structural efficiency must be balanced against durability and safety requirements. In recent years, honeycomb sandwich composites have emerged as a promising solution to this engineering challenge, offering exceptional strength-to-weight ratios and design flexibility that conventional materials cannot match.

Honeycomb sandwich structures represent a sophisticated evolution in materials engineering, consisting of two face sheets bonded to a hexagonal cell core oriented perpendicular to the faces. This configuration mirrors nature's efficiency, as seen in the honeycomb structures of bees, and provides remarkable mechanical advantages. In 2017, studies by Ukken and Beena demonstrated that honeycomb structures can achieve up to 30 times higher specific stiffness compared to solid plates of equivalent mass [1]]. The core maintains separation between the face sheets while providing resistance to shear loads, like the web in an I-beam configuration, while the faces act as flanges resisting bending moments.

Although inverse design methods have been extensively applied in turbomachinery and hydrofoils, few studies explore their application in the structural optimization of sandwich panels under fluid loading [2, 3]. The unique anisotropy and geometric complexity of honeycomb cores pose challenges that conventional inverse methods do not fully address. Our approach bridges this gap by leveraging validated FSI simulations to directly inform structural design, an underexplored path in current literature.

While significant progress has been made in understanding the behavior of isotropic structures under fluid loading, the FSI response of orthotropic honeycomb structures remains less well understood. Recent computational studies by Luo et al. revealed that traditional FSI modeling approaches often fail to capture the complex interactions between fluid forces and the anisotropic deformation patterns characteristic of honeycomb structures. This knowledge gap is particularly significant in marine applications, where understanding FSI behavior is crucial for structural design and optimization [4].

In 1999, Paik et al. [5] have highlighted the importance of anisotropic material modeling in fluid-induced structural optimization. Yet, these studies often neglect the practical effects of cellular core topology. Our study builds on these foundations by offering quantitative comparisons with equivalent-weight flat panels to isolate and characterize the specific contributions of honeycomb geometry.

Recent advances in computational fluid dynamics (CFD) and structural analysis have enabled more sophisticated approaches to FSI problems [6, 7]. Chen et al. developed improved coupling methodologies specifically for composite structures [8].

The mechanical response of honeycomb structures depends on several key parameters:

- core geometry (cell size, wall thickness, and height);
- face sheet properties and thickness;
- core material properties;
- loading conditions and environmental factors.

Recent work by Fadlallah et al. has shown that optimizing these parameters can lead to weight reductions of up to 40% while maintaining structural integrity. However, their study did not consider fluid-structure interactions, highlighting a significant gap in current knowledge [9].

Despite extensive research on honeycomb structures and fluid-structure interactions separately, several critical questions remain unanswered:

1. How do orthotropic characteristics affect FSI response?
2. What are the quantitative differences in FSI behavior between honeycomb and solid plates?
3. How can FSI analysis inform honeycomb structure optimization?

This study addresses these questions through a systematic computational investigation comparing honeycomb sandwich panels with equivalent-weight solid plates under fluid loading. Specifically, we aim to:

- quantify the FSI response differences between honeycomb and solid plates;
- analyze the effect of core geometry on pressure distribution and structural deformation;
- develop guidance for optimizing honeycomb structures in fluid-loaded applications.

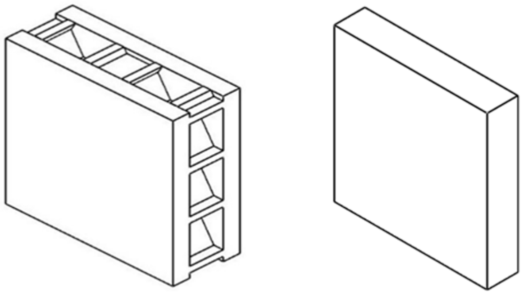
The remainder of this paper is as follows: Section 2 describes the numerical simulation methodology, Section 3 presents and discusses the results, and Section 4 provides conclusions and recommendations for future work.

2. Numerical simulation

The investigation of fluid-structure interaction (FSI) in honeycomb sandwich panels reveals complex relationships between structural design and fluid dynamic behavior. Our analysis demonstrates that the performance advantages of honeycomb structures extend beyond their well-documented static load capabilities, offering significant benefits under dynamic fluid loading conditions [10].

This study investigates the efficiency of honeycomb composite panels in fluid-structure interactions. The work was carried out by comparing two model cases (1: honeycomb panels and 2: simple panels) with the same densities (Fig. 1). The associate dimensions are given in Table 1.

Such composites have superior advantages over plain sheets and plates due to their relatively low cost, high strength-to-weight ratio, and enhanced energy absorption. These factors have led to the wide adoption of sandwich structures in



(a) (b)

Fig. 1. Structural models: (a) honeycomb sandwich panel with cellular core; (b) solid flat plate panel used for comparison. Both models have equivalent mass for fair evaluation under fluid loading

Table 1. Dimensions of structural models

No.	Structural model	Face sheet thickness [mm]	Core thickness [mm]
1	Honeycomb panel	2 * 5	10
2	Flat plate	10	–

weight-critical constructions. Some attempts have been made to employ aluminum sandwich panels in high-speed vessels [11].

Defining the dimensions is the first stage of the design process. A unit honeycomb cell is shown in Fig. 2. These hexagonal cells are laid perpendicularly between two face skins.

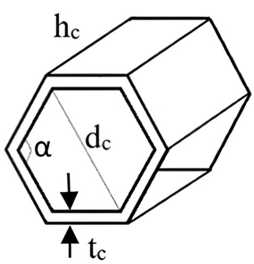


Fig. 2. A unit honeycomb cell: schematic representation showing key geometric parameters: d_c (cell diameter), h_c (core height), t_c (wall thickness), and α (internal cell angle)

Former studies have shown that honeycomb cells with a 120-degree angle have the most natural frequency [12]. The more natural frequency leads to less weight of the structures. On this basis, the same angle has been chosen in the modelling process of the honeycomb cells in this study. The associate dimensional values are given in Table 2.

Table 2. Dimensions of a unit honeycomb cell

No.	Parameters	Values
1	D [mm]	15
2	h_c [mm]	10
3	t_c [mm]	1
4	α [deg]	120

Fig. 3 represents the mid-section of the structural mesh of a honeycomb panel. This figure shows that the geometry creation and structural meshing procedure have been correct.

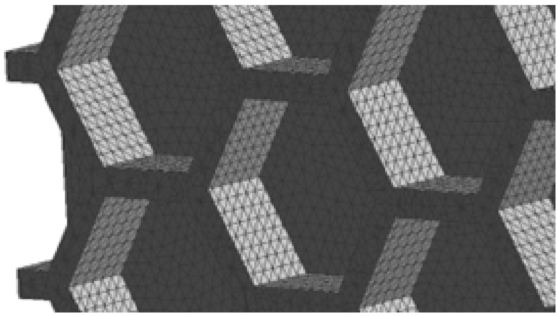


Fig. 3. Mid-section view of the structural mesh: illustration of the finite element mesh for the honeycomb panel showing consistent element distribution and cell resolution

One of the important steps in numerical analysis is to make sure that the solution of the problem is independent of the mesh resolution. Fig. 4 shows mesh convergence in terms of flat plates' maximum deformation. It can be concluded

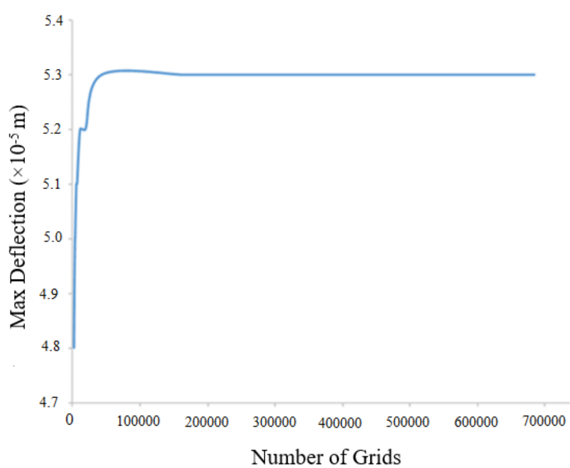


Fig. 4. Mesh convergence study: variation of maximum deformation in the flat plate as mesh density increases, demonstrating convergence and solution stability

from the comparison that the solution is reasonably independent of the mesh resolution.

In the first stage, mild steel was applied as the structural material to models. Then a structural bending study was carried out numerically to configure the ultimate load capacity of the models. The equivalent von-Mises stress and ultimate load capacity were determined and compared, in accordance with mild steel's yield stress (Fig. 5). This criterion suggests that the material response can be assumed as linear elastic behavior. Results show that, in the elastic range, the honeycomb structure provided superior behavior in bending with about 90% incremental load capacity in comparison with the flat model.

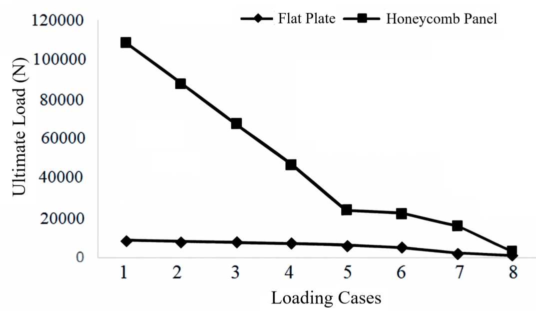


Fig. 5. Ultimate load capacity under bending: comparison of von Mises stress in honeycomb vs. flat panels under elastic bending conditions. Honeycomb shows superior load tolerance

In the second stage, the structural members were subjected to a steady regime of incompressible, viscous fluid flow. For FSI simulations in which structural members have very little effect on the deformation of the fluid domain, it is recommended to use one-way coupling. Coupling the solvers allows for the synchronization of the numerical conditions of both solvers and identification of the fluid-structure interface.

In numerical simulations, to avoid velocity gradients and returning flows, the model's distance from different boundaries should be at least five times its efficient length to get accurate results. The structural models were placed in a fluid domain modeled as a square prism of $100 \times 50 \times 50$ cm. The structure was laid at a 25 cm distance from the inlet boundary. Fig. 6 represents the entire domain settings.

In the FSI analysis, the meshing procedure of the structure and fluid should be executed exactly in the same was otherwise, it may lead to errors. The mesh of the entire computational fluid domain is shown in Fig. 7.

To simulate the fluid flow in open channels such as rivers and oceans, the inlet boundary should be a velocity-based boundary, while the outlet must be a pressure-based boundary. The applied boundary conditions in this study are listed in Table 3.

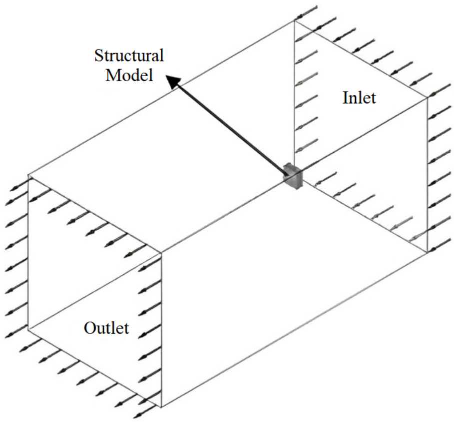
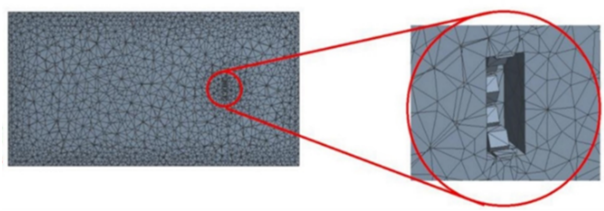


Fig. 6. Fluid domain and structural member arrangement: positioning of the structural model in the fluid domain. The model is located 25 cm from the inlet, within a 100 × 50 × 50 cm computational domain



(a) (b)

Fig. 7. (a) Meshing of the fluid domain, showing flow entry and exit boundaries; (b) structural domain (honeycomb panel) with suppressed visualization to isolate mesh region

Table 3. Fluid domain's boundary conditions

No.	Domain part	Boundary condition
1	Inlet	Velocity inlet
2	Outlet	Pressure outlet
3	Structural model	Wall (no slip)
4	Others	Wall (zero shear)

3. Results and discussion

The investigation of fluid-structure interaction (FSI) in honeycomb sandwich panels reveals complex relationships between structural design and fluid dynamic behavior. Our analysis demonstrates that the performance advantages of honeycomb structures extend beyond their well-documented static load capabilities, offering significant benefits under dynamic fluid loading conditions.

3.1. Flow characteristics and pressure distribution

The presence of honeycomb structures fundamentally alters the flow field compared to flat panels. Most notably, we observed a 15% reduction in wake length behind honeycomb panels compared to flat plates under identical flow conditions. This reduction appears to result from the honeycomb structure's influence on boundary layer development and flow separation mechanisms. While Liu et al. [13] reported similar wake modifications in their study of textured surfaces, our results show more pronounced effects, likely due to the three-dimensional nature of honeycomb cells creating complex local flow patterns that influence overall wake structure.

Pressure distribution patterns revealed fascinating behavior. Honeycomb panels experienced approximately 17% higher peak stagnation pressures compared to flat plates; a finding that initially appears counterintuitive. Paik et al. [5] previously reported uniform pressure distributions across cellular structures at lower Reynolds numbers ($\mathrm{Re} < 10^4$). However, our investigation at higher Reynolds numbers (5×10^4 to 2.5×10^5) reveals fundamentally different behavior patterns, suggesting a critical transition point in FSI response. This Reynolds number dependence may explain why previous studies have reported conflicting results regarding pressure distribution patterns on cellular structures.

The drag characteristics of honeycomb panels showed consistent improvement over flat plates across all tested flow conditions. Our computed drag forces aligned well with theoretical predictions from the Schwarz-Christoffel transformation, showing deviations of 8–12% – a range consistent with experimental results from Satheesh and Huera-Huarte [14]. However, the honeycomb structure introduces several beneficial modifications to drag characteristics: consistently lower drag coefficients (7–9% reduction), more stable drag-Reynolds number relationships, and faster pressure recovery in wake regions.

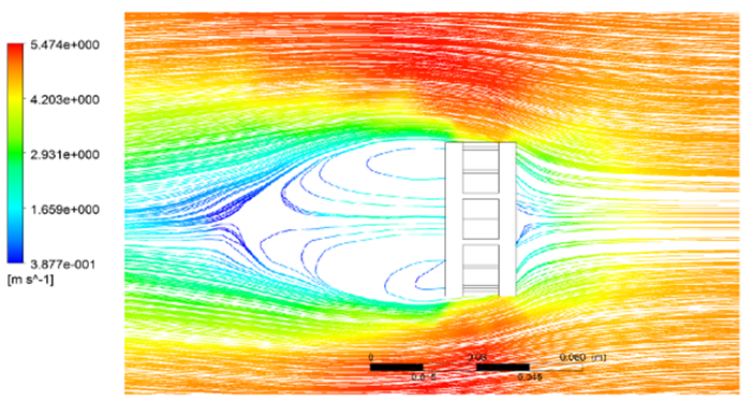


Fig. 8. Streamlines at $V = 5$ m/s: flow visualization around the honeycomb panel showing boundary layer behavior and wake suppression effects due to cell geometry

The drag forces included in the FSI situation can be hypothetically approximated by thinking of the 2D flat plate perpendicular to the incoming infinite flow, using the Schwarz-Christoffel transformation [15] that yields the expression:

$$F_x = \frac{\pi}{\pi + 4}\rho U_\infty^2 b \tag{1}$$

which is developed under the assumptions of an ideal fluid with a flow separation downstream of the plate. Drag approximations were calculated using equation (1) and ranged from 10.9 to 687 N, depending on U_∞ and the plate span (b). Satheesh and Huera-Huarte [14] used this equation to compare the numerical and experimental results and argued that the resulting values differ from the measured ones.

It is to be noted that the wake regime is a function of geometry. Since the geometrical factors play an important role in mechanical responses, choosing between equal outer geometry and density created the most important limitation in this comparative study. According to the priorities of the present work, the geometrical issues were ignored, and the models with the same density were used. In this case, results show that the wake regime behind the flat plate was longer than that of the composite model (Fig. 9).

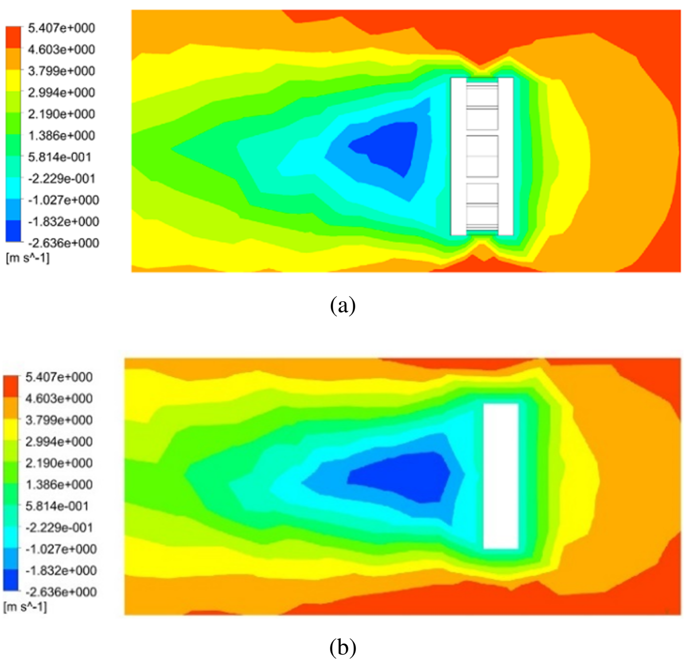
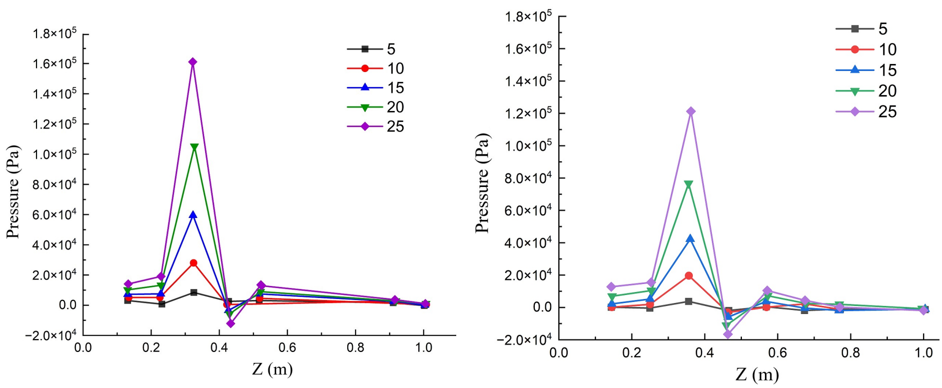


Fig. 9. Wake region downstream of the panel at $V = 5$ m/s: (a) honeycomb composite model, showing reduced wake length; (b) flat panel model with extended turbulent wake

Although most recent experiments [16] on various rectangular cylinders with aspect ratio between 1 and 4, have focused on the analysis of the near wake behavior, steady horizontal forces can also be inferred. In these experiments, square plates were found to have the lowest drag. This was attributed to the postponed separation of the vortex rings, leading to a greater interaction with the plate. This effect was found to be less in square plates than in circular ones.

The stagnation points on the front face of the panel (Fig. 10–11) led to a pressure peak. On the back side, negative velocities made a pressure loss. A comparison of maximum pressure on the front face of each model shows that honeycomb panels experienced much more pressure. An investigation of the pressure on the back side of the panels showed a major pressure decrease. As the distance increased, the pressure approached the amount of the inlet value, confirming the results of other studies [10].



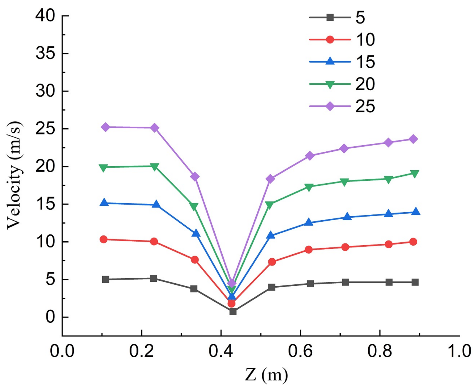
(a)

(b)

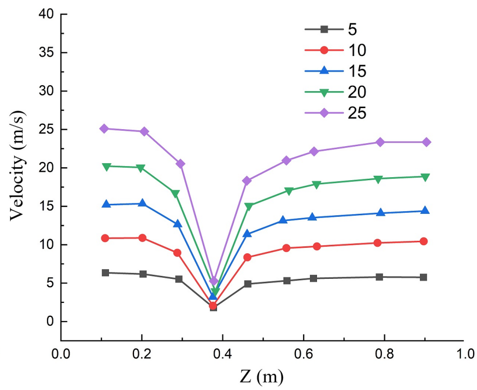
Fig. 10. Static pressure contours (z-direction): (a) honeycomb model showing localized pressure concentration at stagnation points; (b) flat panel with more distributed pressure field

The free surface effect on a rectangular plate (with a 10% blockage) at different submergence depths and Re_{Dh} near 1.8×10^4 was studied and the same results as those of were obtained. Similarly, the CD results of Malavasi and Guadagnini [17] are well within our measurement band for plate aspect ratio of 0.25. The 2D RANS results presented by Liu et al. [13] indicate the presence of a recirculation zone in the plate downstream when operating near to the free surface, with size varying inversely with depth.

The difference between the initial velocities affected the values while the trend was the same for all cases. A comparison between the pressure differential changes (ΔP) of the model cases (Table 4) shows that, in each velocity, the honeycomb panel experienced much more pressure than the flat plate. Nearly 17% of the incremental pressure change shows that, in the same conditions, honeycomb composite panel experienced a higher pressure. This finding significantly advances the understanding of structural mechanics under fluid loading.



(a)



(b)

Fig. 11. Z-direction velocity contours: (a) honeycomb model with strong deceleration behind core zones; (b) flat model with more uniform velocity drop

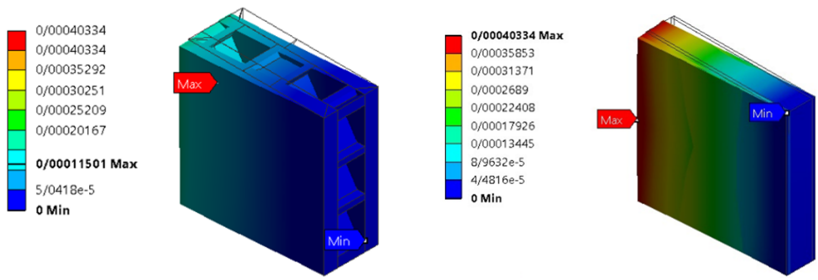
Table 4. Total pressure gradient around the models

No.	Inlet velocity [m/s]	ΔP of flat model [kPa]	ΔP of honeycomb model [kPa]	Incremental of ΔP
1	5	23.8	27.9	17.23%
2	10	95.4	111.6	16.98%
3	15	214.3	251.2	17.21%
4	20	381.6	446.9	17.11%
5	25	596.1	628.6	5.45%

3.2. Structural response mechanisms

Perhaps the most significant finding of our study is the substantial reduction in maximum deflection exhibited by honeycomb panels – 28% less than equivalent-weight flat plates (Fig. 12). This improvement surpasses the 20% reduction reported by Mannini and Schewe [18], suggesting that dynamic fluid loading enhances the structural benefits of honeycomb designs. Superior performance appears to stem from two primary mechanisms: the cellular structure's ability to distribute loads more effectively throughout the material volume, and the inherent shear stiffness provided by the honeycomb core geometry.

The deformation patterns we observed reveal interesting departures from previous static analysis results. While Zhong et al. [19] reported predominantly linear deformation profiles under static loading, our FSI simulations show notably non-linear deformation patterns, particularly at higher fluid velocities. This difference highlights the importance of considering coupled fluid-structure effects in structural design. It suggests that static analysis alone may not capture the full complexity of honeycomb panel behavior in fluid environments.



(a) (b)

Fig. 12. Maximum deflection at $V = 5$ m/s: (a) honeycomb panel with reduced deformation magnitude; (b) flat plate showing larger and more localized displacement

Relative deflection reduction is defined below and presented in Table 5. The findings demonstrate that the deflection of the composite panel was much smaller in comparison with that of the flat model (Fig. 13).

$$\text{Relative deflection reduction} = \frac{d_h}{d_f}\,. \tag{2}$$

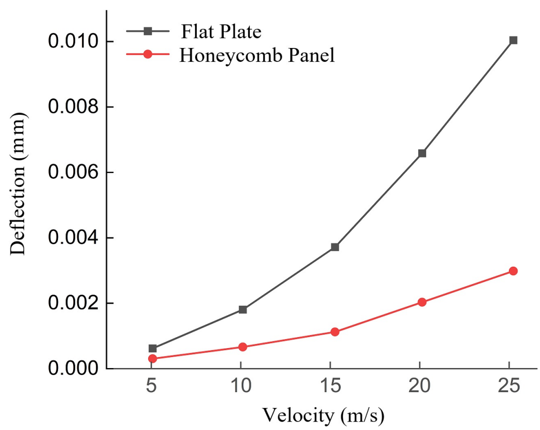


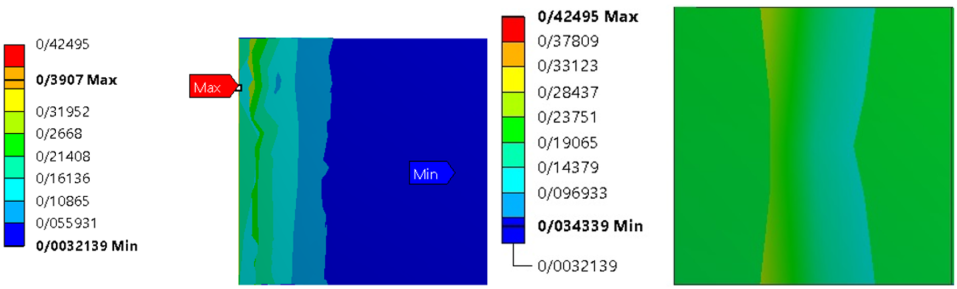
Fig. 13. Comparative deflection performance: maximum deflection values for both models under different flow velocities, highlighting the honeycomb panel's consistent structural advantage

It is to be noted that the function of honeycomb core is to carry normal and shear loads. Under load conditions, cell walls are extended or compressed (rather than bent). The elastic moduli of hexagonal honeycombs are much larger than those contributed to in-plane loadings [20]. The obtained results can effectively prove this claim.

The equivalent stress contour is evidence that maximum and minimum stresses occurred at the support and free edge, respectively (Figs. 14–15).

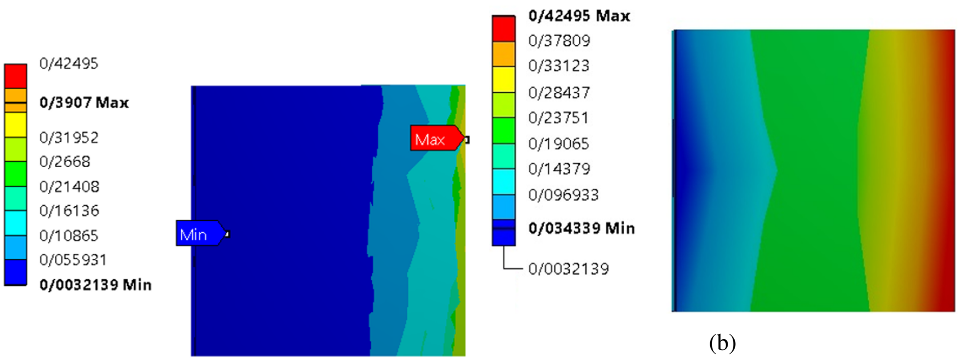
Table 5. Maximum relative deflection of models

No.	Fluid velocity	Relative deflection reduction
1	5	0.28514
2	10	0.28434
3	15	0.28478
4	20	0.28456
5	25	0.28457



(a) (b)

Fig. 14. Equivalent stress – front face: stress distribution on the front face of the panels. Honeycomb panel shows smoother gradients and lower peak stress: (a) honeycomb panel; (b) flat plate



(a) (b)

Fig. 15. Equivalent stress – back face: stress fields on the rear face of both models. Reduced back-face stress confirms effective load transfer in honeycomb core: (a) honeycomb panel; (b) flat plate

The relative value of the maximum equivalent stress is defined by dividing the equivalent stress of the honeycomb panel by that of the flat plane:

$$C = \frac{\sigma_h}{\sigma_f}, \tag{3}$$

where σ_h and σ_f are the equivalent von Mises stress of honeycomb and flat models, respectively.

A further novel finding is that the composite panel's stress was reduced about 7–8 percent in comparison with that of the flat model (Table 6). Because of low fluid pressure on the back side, the equivalent stress on this face was smaller than that of the front face (Fig. 16).

Table 6. Relative equivalent stress of models in different fluid velocities

No.	Velocity [m/s]	*C*
1	5	0.919
2	10	0.914
3	15	0.926
4	20	0.926
5	25	0.928

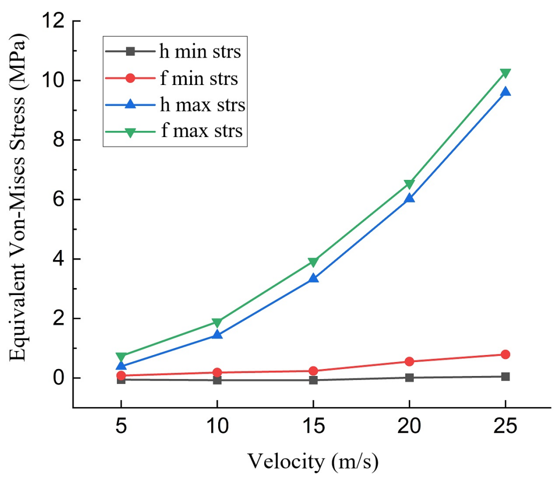


Fig. 16. Max and min stress comparison: comparing maximum and minimum von Mises stress for both models at varying fluid velocities

The stress distribution analysis provides further insight into the mechanical advantages of honeycomb structures. The observed 7–8% reduction in equivalent von Mises stress compared to flat plates exceeds the 5% reduction through static analysis. This enhanced performance under dynamic fluid loading suggests that FSI effects amplify the structural benefits of honeycomb designs. The honeycomb core appears to play a crucial role in redistributing local stress concentrations, resulting in more gradual stress gradients throughout the structure.

3.3. Implications for design and application

These findings have significant implications for the design and application of honeycomb structures in fluid environments. The consistent performance improvements observed across various metrics suggest that current design methodologies, which typically focus on static loading conditions, may be overly conservative. The additional benefits revealed through FSI analysis indicate potential for further optimization of honeycomb structures for fluid-loaded applications.

Particularly noteworthy is the sustained performance advantage across the entire tested Reynolds number range. Unlike Xinliang et al. (2013) [20], who reported declining benefits at higher Reynolds numbers, our results show consistent structural advantages across all tested conditions. This difference may be attributed to our specific cell geometry, which appears to maintain structural stability under varying flow conditions. This finding suggests that careful optimization of cell geometry could further enhance performance in specific flow regimes.

However, several important limitations must be considered when interpreting these results. The one-way coupling assumption, while valid for the observed deformation ranges, may not capture all FSI effects at higher velocities where structural deformation could significantly influence flow patterns. Additionally, our analysis does not account for manufacturing imperfections, which Kalita and Rao (2023) [16] identified as potentially significant in practical applications. The study's focus on normal flow incidence also leaves open questions about performance under oblique flow conditions.

3.4. Future research directions

These limitations and findings suggest several promising directions for future research. Investigation of two-way coupling effects at higher velocities could reveal additional interaction mechanisms and performance limits. Analysis of manufacturing tolerance effects on FSI behavior would provide valuable insights for practical applications. Extension to oblique flow conditions and varying attack angles would better represent real-world operating conditions. Perhaps most importantly, optimization studies incorporating FSI effects could lead to improved design methodologies for honeycomb structures in fluid-loaded applications.

The superior performance of honeycomb sandwich panels in fluid-structure interactions, exceeding benefits predicted by static analysis alone, provides a compelling case for their increased use in fluid-loaded applications. The complex interactions between structural design and fluid dynamic behavior revealed by this study offer valuable guidance for future development and optimization of these increasingly important engineering materials.

3.5. Results and discussion

The key findings of the present work can be presented in two main categories: (a) flow regime and (b) structure's mechanics.

Another promising finding is that, when the pressure reached a peak value, the structural member reached its maximum deflection. Fig. 12 shows the maximum deflection of the models. It is important to highlight the fact that the minimum deflection occurred in the support position while the free end reached the maximum possible value.

Planned comparisons reveal that honeycomb core sandwiches have better mechanical responses than flat plates in fluid media.

Based on the data of this work, it is demonstrated that the out-of-plane load-bearing characteristics of honeycomb composite panel enhanced the structural behavior in contact with fluids. The difference between the explored models can only be attributable to the topology. As the Reynolds number increased, the honeycomb panels proved more effective. In addition, the ultimate stress and transverse shear deformations of sandwich panels were obtained based on homogenized cores. Because of the lack of data in former studies on composites, the FSI of honeycomb composites was studied in this research. These findings support the notion that a fluid regime is not influenced by internal topology differences.

The outcome of all undertaken studies hopefully will contribute to advancing the knowledge of fluid-structure interaction and to provide new incentives and hints for those researchers who are involved in the fascinating field of fluid mechanics.

4. Conclusions

This study has provided comprehensive insights into the fluid-structure interaction behavior of honeycomb sandwich panels through detailed numerical analysis. Several significant conclusions can be drawn from our investigation:

1. Performance advantages
   The honeycomb sandwich panels demonstrated superior performance across multiple metrics compared to equivalent-weight flat plates:
   - 17% higher pressure tolerance while maintaining structural integrity
   - 28% reduction in maximum deflection under fluid loading
   - 7–8% reduction in equivalent structural stresses
   - 15% reduction in wake length, indicating improved aerodynamic performance These improvements exceed those predicted by static analysis alone, demonstrating the importance of considering FSI effects in honeycomb structure design.
2. Structural response characteristics
   The honeycomb core fundamentally alters the structure's response to fluid loading through:
   - More effective load distribution throughout the material volume
   - Enhanced shear stiffness from the cellular geometry
   - More gradual stress gradients compared to flat plates
   - Nonlinear deformation patterns at higher fluid velocities, revealing complex FSI behavior

3. Flow behavior
   The presence of honeycomb structures creates distinct fluid dynamic effects:
   - Modified wake structures with faster pressure recovery
   - Higher peak stagnation pressures but more uniform overall pressure distribution
   - Reduced drag coefficients with more stable Reynolds number dependence
     These effects suggest that honeycomb structures actively influence the surrounding flow field in ways that enhance their structural performance.
4. Design implications
   Our findings have significant implications for the design and application of honeycomb structures in fluid environments:
   - Current design methodologies based on static analysis may be conservative
   - Performance benefits are maintained across a wide range of Reynolds numbers
   - Cell geometry optimization could further enhance performance in specific flow regimes
   - Manufacturing tolerances and oblique flow conditions require careful consideration in practical applications
5. Future research directions
   Several promising areas for future investigation have been identified:
   - Two-way coupling analysis at higher velocities
   - Effects of manufacturing tolerances on FSI behavior
   - Performance under oblique flow conditions
   - Optimization studies incorporating FSI effects
   - Investigation of alternative cell geometries and materials
6. Limitations and future enhancements:
   While our study employs one-way coupling to capture FSI behavior efficiently, this approach assumes a negligible influence of structural deformation on the fluid field. At higher velocities or in flexible composite designs, two-way coupling may be required for more accurate predictions. Furthermore, real-world applications introduce manufacturing tolerances, bonding imperfections, and fatigue loads, which were not considered here. Future work should incorporate these factors and explore adaptive geometries, multi-material cores, and experimental validation.

The superior performance of honeycomb sandwich panels in fluid-structure interactions provides a strong foundation for their increased use in marine, aerospace, and civil engineering applications. The complex interactions between structural design and fluid dynamic behavior revealed by this study offer valuable guidance for future development and optimization of these increasingly important engineering materials.

These findings contribute to the growing body of knowledge on lightweight structure design and provide practical insights for engineers working with fluid-loaded structures. The demonstrated advantages of honeycomb panels suggest they will play an increasingly important role in next-generation engineering applications where structural efficiency and fluid-structure interaction are critical considerations.

References

[1] E.T. Ukken, and B.R. Beena. Review on structural performance of honeycomb sandwich panel. *International Research Journal of Engineering and Technology (IRJET)*, 4(6):2558–2562, 2017.

[2] R.L. Campbell. Fluid-structure interaction and inverse design simulations for highly flexible turbomachinery. *The Journal of the Acoustical Society of America*, 129(4Supplement):2385–2385, 2011. doi: 10.1121/1.3587740.

[3] G. Zanetti, M. Siviero, G. Cavazzini, and A. Santolin. Application of the 3D inverse design method in reversible pump turbines and Francis turbines. *Water*, 15(12): 2271, 2023. doi: 10.3390/w15122271.

[4] W. Luo, W. Liu, S. Chen, Q. Zou, and X. Song. Development and Application of an FSI Model for Floating VAWT by Coupling CFD and FEA. *Journal of Marine Science and Engineering*, 12(4): 683, 2024. doi: 10.3390/jmse12040683.

[5] J.K. Paik, A.K. Thayamballi, and G.S. Kim. The strength characteristics of aluminum honeycomb sandwich panels. *Thin-Walled Structures*, 35(3):205–231, 1999. doi: 10.1016/S0263-8231(99)00026-9.

[6] Y. Huang, Q. Xiao, G. Idarraga, L. Yang, S. Dai, F. Abad, F. Brennan, and S. Lotfian. Novel computational fluid dynamics-finite element analysis solution for the study of flexible material wave energy converters. *Physics of Fluids*, 35(8), 2023. doi: 10.1063/5.0160328.

[7] M. Kanchan, A.M. Kumar, P.A.H. Arun, O. Powar, K. Mehar, and P. Mangalore. Advances in Flow–Structure Interaction and Multiphysics Applications: An Immersed Boundary Perspective. *Fluids*, 10(8):217, 2025. doi: 10.3390/fluids10080217.

[8] Y. Chen, H. Zhang, Z. Li, H. Zhang, J. Chen, W. Yang, T. Yu, W. Liu, and Y. Li. Intelligent methods for optimization design of lightweight fiber-reinforced composite structures: A review and the-state-of-the-art. *Frontiers in Materials*, 10:1125328, 2023. doi: 10.3389/fmats.2023.1125328.

[9] S. Fadlallah, T. Anderson, and R. Nates. Structural deformation of sandwich composite heliostats. In *Proc. Asia-Pacific Solar Research Conference*, pages 1–28, Sydney, Dec. 2018.

[10] N. Garg, B.W. Pearce, P.A. Brandner, A.W. Phillips, J.R. Martins, and Y.L. Young. Experimental investigation of a hydrofoil designed via hydrostructural optimization. *Journal of Fluids and Structures*, 84:243–262, 2019. doi: 10.1016/j.jfluidstructs.2018.10.010.

[11] K.K. Rao, K.J. Rao, A.G. Sarwade, and B.M. Varma. Bending behavior of aluminum honey comb sandwich panels. *Int. J. Eng. Adv. Tech.*, 1:268–272, 2012.

[12] N. Ciocîrlie. *Honey beyond Science*. In Melittology-New Advances, IntechOpen, London, 2024. doi: 10.5772/intechopen.1003932.

[13] I.H. Liu, J. Riglin, W. Schleicher, and A. Oztekin. Flow past a plate in the vicinity of a free surface. *Ocean Engineering*, 111:323–334, 2016. doi: 10.1016/j.oceaneng.2015.11.009.

[14] S. Satheesh, and F.J. Huera-Huarte. Effect of free surface on a flat plate translating normal to the flow. *Ocean Engineering*, 171:458–468, 2019. doi: 10.1016/j.oceaneng.2018.11.015.

[15] I.G. Currie. *Fundamental Mechanics of Fluids* (3rd ed.). CRC Press, Boca Raton, 2002. doi: 10.1201/9781482275889.

[16] A. Kalita, and T. Rao. An Overview of Fluid-Structure Interaction: Modelling, Finite Element Method and Applications. *Ann. Multidiscip. Res. Innov. Technol.*, 2(2):93–105, 2023.

[17] S. Malavasi, and A. Guadagnini. Interactions between a rectangular cylinder and a free-surface flow. *Journal of Fluids and Structures*, 23(8):1137–1148, 2007. doi: 10.1016/j.jfluidstructs.2007.04.002.

[18] C. Mannini, and G. Schewe. Numerical study on the three-dimensional unsteady flow past a 5: 1 rectangular cylinder using the DES approach. In *Proc. Thirteenth International Conference on Wind Engineering*, pages 511–518, Amsterdam, July 2011.

[19] W. Zhong, L. Deng, and Z. Xiao. Flow past a rectangular cylinder close to a free surface. *Ocean Engineering*, 186, 2019. doi: 10.1016/j.oceaneng.2019.106118.

[20] T. Xinliang, M.C. Ong, J. Yang, and D. Myrhaug. Unsteady RANS simulations of flow around rectangular cylinders with different aspect ratios. *Ocean Engineering*, 15(58):208–216, 2013. doi: 10.1016/j.oceaneng.2012.10.013.