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作品名稱　Design and Simulation of a Honeycomb Sandwich Panel as a Heat-resistant and Durable Construction Material

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Design and Simulation of a Honeycomb Sandwich Panel as a Heat-resistant and Durable Construction Material

ABSTRACT

One of the main factors that contribute to fire incidents and the excessive heat people feel during a heat wave is the building materials used, and one such material that possesses durable and heat-resistant properties is sandwich panels. A possible structure that can be used to model sandwich panels is honeycomb structures; however, further research has yet to be conducted on its applications as a heat-resistant urban construction material. This study aims to design a three-dimensional model of a honeycomb sandwich panel and simulate its performance under different thermal and structural stressors. A 3D model of the honeycomb sandwich panel was generated using Autodesk Fusion 360. Then, multiple versions of the panel were generated with varying heat-resistant core materials—namely, aluminum, nickel, nickel-copper alloy 400, and copper—along with polystyrene as the core material for the control model. The following properties of every panel were assessed using finite element analysis (FEA): static deformation, stress distribution, strain distribution, total heat flux, and thermal gradient. Results showed that when subjected to varying structural loads (2 kN, 5 kN, 7 kN), the nickel-core panel demonstrated the best results in terms of static deformation and strain distribution due to its relatively lower deformation and elongation values, respectively. Meanwhile, under the same structural loads, the aluminum-core panel performed better than other core materials in terms of stress distribution due to it having the relatively highest difference between its simulated von Mises stress and its yield strength. The honeycomb sandwich panels have also shown to possess heat-resistivity when subjected to a thermal load of 90°C, with polystyrene being the most promising material overall in terms of heat-resistance due to its relatively lower heat flux and thermal gradient. The results from this study would contribute to future research on honeycomb sandwich panels and may be used in real-life applications.

Keywords: *Autodesk Fusion 360, finite element analysis, fire-resistant construction materials, honeycomb sandwich panels*

1. Introduction

Fire disasters have been a recurring global concern due to their negative impact on the ecosystem and society [16]. In the Philippines, the number of nationwide fire incidents has increased by over 270% throughout the past 10 years, with reported disasters growing from approximately 4800 to 13000 from 2012 to 2022 [19, 20]. One of the main factors that contribute to urban fire incidents is the building materials available, with the combustion of synthetic and other highly flammable materials engendering rapid fire growth [23].

As a preventive measure for this hazard, construction materials that are capable of limiting flame spread should be utilized, such as wall linings, insulation, and physical barriers (e.g., cement, stone, and concrete walls) [6]. However, with the current global trends and scarcity of resources, there is an increased demand for building resources that are more lightweight, durable, and efficient [21]. This highlights the need for a light and accessible construction material that can not only support large structures but also help mitigate fire spread.

Previous studies have investigated possible alternative materials that possess these qualities — one such material is sandwich panels. Sandwich panels are materials made of two or more high-strength outer layers (face sheets) and a low-density inner layer (core) [7]. They are commonly used in the aviation, military, and automobile industries because of their superior strength, insulation, and impact resistance [10]. However, extensive research has yet to be conducted on the fire-resistant capabilities of this material [4]. Thus, researching other fire-retardant materials and structures that can be used to model sandwich panels is of interest, one of which is honeycomb structures.

Honeycomb structures, inspired by the same formations built by bees, are made of hexagonal cells put alongside each other to create a honeycomb face [5]. They are used to create honeycomb sandwich panels, with the actual honeycomb structures perpendicular to the face sheets. Past studies have investigated and proved the weight-sensitive, flexural, and damping properties of this material [17]. Moreover, research has demonstrated their good fire performance properties, including long ignition times and low heat release, in commercial applications such as aircraft manufacturing [22]. However, further research has yet to be conducted on its applications as a fire-resistant urban construction material.

The main objective of this study is to design a 3-dimensional model of a honeycomb sandwich panel and simulate its performance under different thermal and structural stressors to determine its efficacy as a fire-resistant and durable construction material.

Specifically, this research also aims to assess the structural and fire-resistant capacities of the designed model through computerized structural and thermal analytical simulations. Lastly, it aims to determine the effects of using various core materials and determine the optimum material that satisfies the given constructional and thermal parameters.

2. Method and Experiment Details

Development of 3D Models of Honeycomb Sandwich Panels

A three-dimensional model of the honeycomb sandwich panel was generated using the Autodesk Fusion 360 platform [14]. First, the honeycomb-structured core was modeled; then, the adhesive and face sheets were added on either side. As adapted from the methods of Irwin et al. (2021) and Abhinav et al. (2021), the panel had the following dimensions: (a) Hexagonal Cell: Hexagon edge length=3.5 mm; Edge thickness=0.68mm; Height=15mm, and (b) Facing Sheet: Sheet thickness=2mm; Width: 70mm; Length: 140mm [10, 1].

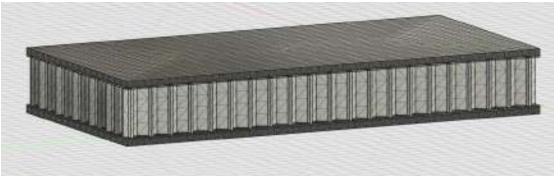

Figure 1. A honeycomb sandwich panel construction.

The face sheets were made of carbon fiber reinforced polymer (CFRP) — a material that has previously been used in honeycomb sandwich panel production and is known for its low weight-to-strength ratio, mobility, durability, and lightweight properties [28]. Additionally, the adhesive sheet used was an epoxy adhesive [27]. Multiple versions of the model were generated with different core materials that have been proven to possess fire-resistant properties, namely aluminum, copper, and nickel, and nickel-copper alloys [13, 1]. This was done to help identify which material is optimum for fire resistance and structural integrity.

As a basis for the significance of the measured properties of the experimental models, a control model was made with polystyrene (PS) as the core material. It is a readily available sandwich panel utilized for its thermal insulation properties but is highly flammable and not as durable as other sandwich panels in the market [3].

Integration of 3D Models into Autodesk Fusion 360 Software

Before uploading the honeycomb sandwich panel geometry to the software, the engineering data for the panels' materials was identified. This includes their density, Young's modulus, yield strength, tensile strength, fracture toughness, melting temperature, specific heat capacity, thermal conductivity, and thermal expansion. The existing material library of Autodesk Fusion 360 already contains the aforementioned materials, including their specific material properties.

Mesh Generation of Integrated 3D Models

The generated 3D model was then uploaded to the software, and a meshed panel version was generated. This was done to divide the panel into smaller individual elements that are regularly shaped and more manageable to analyze. The meshing process involves creating a collection of these elements with certain coordinates in the simulation space to define the irregularly shaped model, which was done automatically by the software [18].

Assessment of 3D Models via Finite Element Analysis

The finite element analysis (FEA) was utilized to test all the 3D model versions, which was conducted with Autodesk Fusion 360 [8]. Specifically, the following properties were assessed: static deformation, stress distribution, strain distribution, total heat flux, and thermal gradient.

Simulation of Structural Properties

Static deformation (measured in mm), stress distribution (measured in MPa), and strain distribution (measured in mm/mm) are properties under FEA that quantify the structural characteristics of the panels by measuring their performance under certain structural stressors [2].
These were evaluated via static structural analysis, specifically on the total deformation, equivalent elastic strain, and equivalent stress. A uniformly distributed load of 1.5 KN was applied to conduct the static structural deformation analysis.

Simulation of Thermal Properties

On the other hand, total heat flux (measured in W/mm^2) and total thermal gradient (measured in °C/mm), also under FEA, are properties that quantify the material's thermal characteristics [13]. Steady state heat transfer analysis and transient thermal analysis was used to measure the thermal stress distributions of the panel. The face sheets of the panel were subjected to a surface temperature of 90°C for a span of 30 seconds to conduct the thermal analysis tests. The aforementioned simulated tests were conducted amongst all panels in triplicates to observe possible variations in the results.

3. Result and Discussion

Static Deformation

To measure static deformation, loads of 2-kN, 5-kN, and 7-kN were carried out in Autodesk Fusion 360 at a constant vertical downward force distributed equally relative to the dimensions of the model. Figure 2 shows the resulting simulation runs of the static deformation simulations of the varying honeycomb sandwich panels under a load of 2-kN in Autodesk Fusion 360.

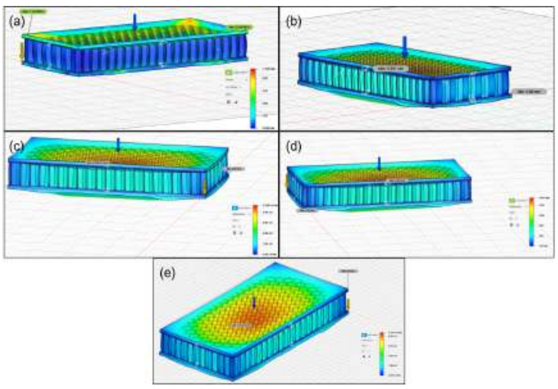

Figure 2. Static deformation simulation results of a honeycomb sandwich panel undergoing 2-kN constant vertical downward load with core: (a) polystyrene; (b) aluminum; (c) nickel-copper alloy 400; (d) copper; (e) nickel.

A honeycomb sandwich panel, regardless of core and cell size, is expected to have similar behavior when the same amount of load is applied to it, wherein the displacement curve would increase linearly until it reaches a peak load [15]. It is also expected that after attaining a critical strain from the constant force applied, the cell wall collapses due to elastic buckling, plastic yielding, creep, or brittle fracture [2].

Figure 3 displays the collected results of the maximum deformations of the honeycomb sandwich panels with varying core materials under a range of loads.

Table 1. Measured static deformation of models in mm.

Core Material	Maximum Deformation Under Varying Loads (mm)		
	2kN	5kN	7kN
Polystyrene (Control)	0.006	0.016	0.022
Aluminum	0.001	0.003	0.005
Nickel-Copper Alloy 400	0.000	0.002	0.003
Copper	0.001	0.003	0.004
Nickel	0.0008	0.002	0.003

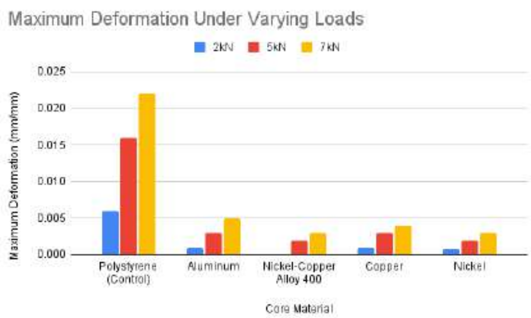

Figure 3. Measured maximum static deformation of models under varying loads.

As shown in Figure 3, a nickel core is expected to perform better than other core materials in terms of static deformation due to its relatively lower maximum deformations across all loads, meaning a honeycomb sandwich panel with a nickel core material is expected to deform less when subjected to load. The results of the nickel core may also be owed to its high-temperature strength, creep resistance, fatigue life, and corrosion resistance, all of which contribute to its deformation resistance [12]. Additionally, a study by Remennikov et al. (2019) has shown that nickel on honeycomb-like structures exhibits exceptional strength and stiffness while being lightweight [24].

<u>*Stress Distribution*</u>

Besides the static deformation of these metals, stress distribution was also simulated in this study. Stress distribution determines the flexural strength of the honeycomb sandwich panels, and was calculated using the bending theory and the von Mises stress simulated in the Autodesk Fusion 360 Software [2, 9, 26]. Specifically, the von Mises stress was used to predict how materials yield under uniaxial tensile stressors [11].

This study mimics that of Gpoichand et al. (2013) in which a sandwich panel is simulated multiple times under different loads in kilonewtons (kN), and the stress distribution of the sandwich panel is measured in Megapascals (MPa) [9]. Figure 4 displays the resulting simulation runs of the stress distribution simulations of the different honeycomb sandwich panels in the Autodesk Fusion 360 software.

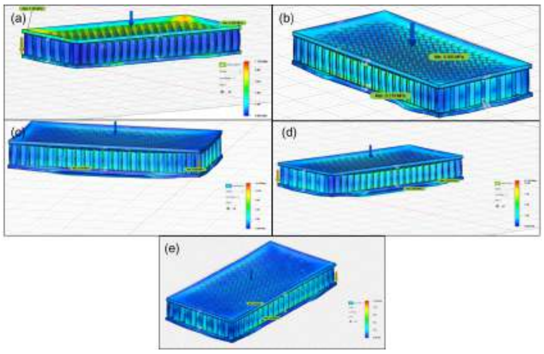

Figure 4. Stress distribution analysis simulation reflecting the stress distribution of the honeycomb sandwich panel under a 2-kN load in with core: (a) polystyrene; (b) aluminum; (c) nickel-copper alloy 400; (d) copper; (e) nickel.

Figure 4 shows the measured von Mises stress (σ_v) of the honeycomb sandwich panels with varying core materials under different amounts of load, namely 2-kN, 5-kN, and 7-kN. Furthermore, Table 3 shows the yield strength (σ_y) of the panels along with the difference (d) of the von Mises Stress and the yield strength given with the formula below.

$$d = \sigma_y - \sigma_v \quad (1)$$

This is taken because yielding occurs when the equivalent stress (measured as the von Mises stress) reaches the yield strength of the material under simple tension (measured as yield strength) [11]. Hence, a negative difference between the yield strength and measured von Mises stress would mean that the material would yield or break under the subjected loads.

Table 2. Measured von Mises stress of models in Megapascals.

Core Material	von Mises Stress Under Varying Loads (MPa)		
	2kN	5kN	7kN
Polystyrene (Control)	7.106	17.763	24.867
Aluminum	8.225	20.554	28.774
Nickel-Copper Alloy 400	14.40	35.965	49.923
Copper	10.545	26.338	36.866
Nickel	15.498	38.708	54.182

Table 3. Yield strength of the core materials with the corresponding difference in Megapascals.

Core Material	Yield Strength (MPa)	von Mises Stress Under Varying Loads (MPa)		
		2kN	5kN	7kN
Polystyrene (Control)	28.8	21.694	11.037	3.933
Aluminum	276	267.775	255.446	247.226
Nickel-Copper Alloy 400	240	225.6	204.035	190.077
Copper	33	22.455	6.662	-3.866
Nickel	59	43.502	20.292	4.818

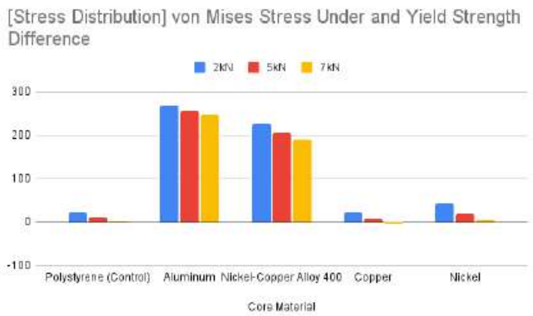

Figure 5. Measured difference between von Mises stress and yield strength of models under varying loads.

As shown in Figure 5, the aluminum core performed better than other core materials in terms of stress distribution due to it having the relatively highest measured difference for every amount of load tested. These results again follow the fact that the aluminum's physical properties allow for its malleability and flexibility as a structural material under a certain amount of load [25].

Strain Distribution

The strain distribution of the honeycomb sandwich panel models was also determined through FEA. As adapted from the study of Ali et al. (2021), loads of 2-kN, 5-kN, and 7-kN were also carried out to the panels [2]. To quantify strain distribution, the maximum elongation of the model or the deformation of the model along the x-axis caused by the load was measured in millimeters per millimeter (mm/mm). Figure 6 shows the resulting simulation runs of the strain distribution simulation of the honeycomb sandwich panels under a load of 2-kN in the Autodesk Fusion 360.

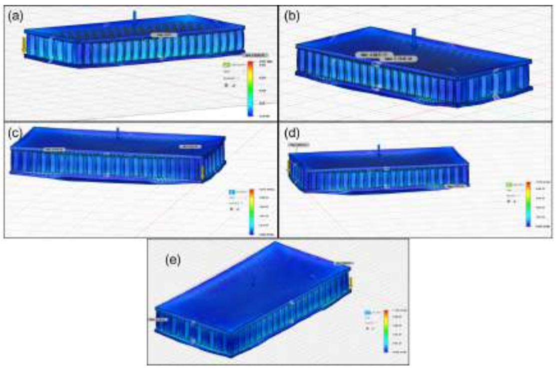

Figure 6. Strain distribution analysis simulation reflecting the strain distribution of a nickel honeycomb sandwich panel in Autodesk Fusion 360 with cores: (a) polystyrene; (b) aluminum; (c) nickel-copper alloy 400; (d) copper; (e) nickel.

Moreover, Figure 7 shows the measured maximum elongation (deformation of the model along the x-axis) in mm/mm of the honeycomb sandwich panel models with varying core materials.

Table 4. Measured maximum elongation (strain distribution) of models in mm/mm.

Core Material	**Maximum Elongation (Strain Distribution) Under Varying Loads (mm/mm)**		
	2kN	5kN	7kN
Polystyrene (Control)	0.001	0.003	0.004
Aluminum	0.0005766	0.001	0.002
Nickel-Copper Alloy 400	0.0004014	0.001	0.001
Copper	0.0004705	0.001	0.002
Nickel	0.0003766	0.000943	0.001

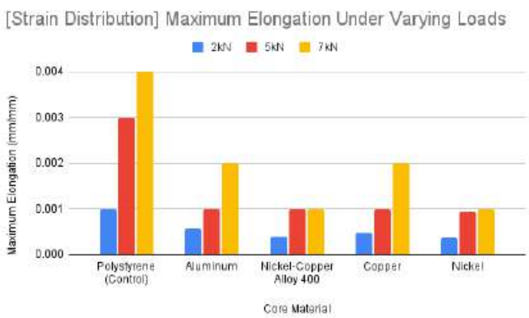

Figure 7. Measured maximum elongation of models under varying loads.

Based on these results and the nickel material's natural properties of high-temperature strength, creep resistance, fatigue life, and corrosion resistance, the honeycomb sandwich panel with a nickel alloy core would perform the best out of the other core materials with its low strain distribution. The normal elastic strain results noticed for sandwich structure with 0.5 mm thickness maximum elongation was 0.00098 mm/mm [2]; however, the values from the simulations have exhibited much lower values. Though all panels are in the threshold set by the study of Ali et al. (2021), the nickel-core sandwich panel still demonstrated the lowest, suggesting a good structural integrity in terms of strain distribution [2].

Assessment of Thermal Properties via Finite Element Analysis

Table 5 shows the specific heat (in J/(kg · °C)) and thermal conductivity (in W/(mm · °C)) of the varying core materials, based on the study materials' engineering data on the Autodesk Fusion 360 software.

Table 5. Measured specific heat specific heat (in J/(kg · °C)) and thermal conductivity (in W/(mm · °C)) of core materials.

Core Material	**Specific Heat (J/(kg · °C))**	**Thermal Conductivity (W/(mm · °C))**
Polystyrene (Control)	2144.00	2.200E-04
Aluminum	897.00	0.23
Nickel-Copper Alloy 400	502.00	0.401
Copper	450.00	0.401
Nickel	456.00	0.079

As seen in Table 5, polystyrene (the control material) is the most promising core in terms of thermal properties due to its high specific heat and very low thermal conductivity, especially in comparison to the types of metals to be tested.

To further assess the thermal capabilities of the models, total heat flux (in W/mm^2) and total thermal gradient (in °C/mm) was measured. As adapted from the study of Kakade and Ghuge (2017), the top face sheet of the panel was subjected to a thermal load of 90°C to conduct the thermal analysis tests [13].

Total Heat Flux

Steady state heat transfer, a test under FEA, was used to measure the heat flux distribution of the panels in W/mm^2. It determines the total rate of heat transfer per unit area. Figure 8 shows the total heat flux plots of the honeycomb sandwich panels with varying core materials.

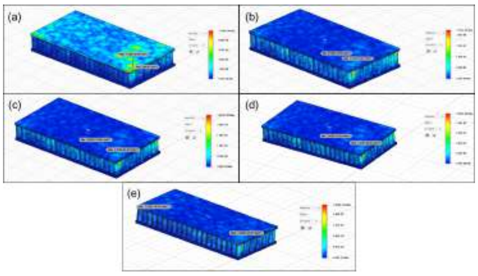

Figure 8. Total heat flux plot of a honeycomb sandwich panel in Autodesk Fusion 360 with the following core materials: (a) polystyrene; (b) aluminum; (c) nickel-copper alloy 400; (d) copper; (e) nickel.

Meanwhile, Table 6 and Figure 9 show the total heat flux in W/mm^2 of the honeycomb sandwich panel models with varying core materials.

Table 6. Measured total heat flux of models in W/mm^2.

Core Material	Minimum Heat Flux	Maximum Heat Flux
Polystyrene (Control)	4.626E-11	7.459E-06
Aluminum	6.536E-10	2.214E-04
Nickel-Copper Alloy 400	4.638E-10	2.453E-04
Copper	4.638E-10	2.453E-04
Nickel	7.579E-10	2.036E-04

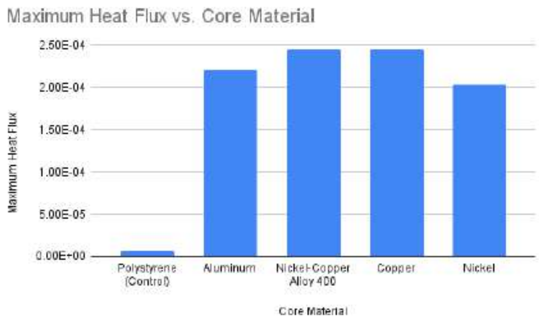

Figure 9. Measured maximum total heat flux of models.

As shown in Figure 9, the panel with polystyrene as its core material yielded the lowest minimum and maximum heat flux, making it the best core in terms of total heat flux. The polystyrene material having the highest specific heat and lowest thermal conductivity means that it requires more effort for a change in temperature, and it is less conductive and more resistant to thermal radiation [3]. Because of this, the results of the heat flux simulation align with polystyrene's properties.

Total Thermal Gradient

On the other hand, transient thermal analysis was used to quantify the thermal gradient, to be measured in °C/mm, which describes how the panel reacts to the chosen surface temperature by identifying the rate at which the temperature of the panel changes per unit distance.

Figure 10 shows the total thermal gradient plots of the honeycomb sandwich panels with varying core materials.

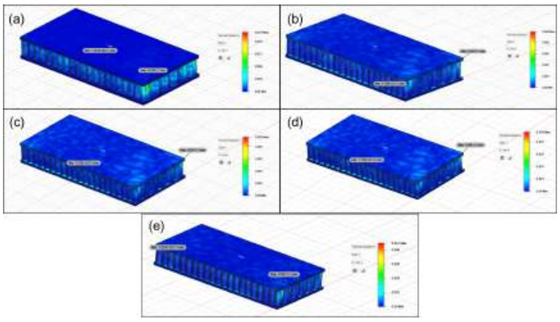

Figure 10. Total thermal gradient plot of a honeycomb sandwich panel in Autodesk Fusion 360 with the following core materials: (a) polystyrene; (b) aluminum; (c) nickel-copper alloy 400; (d) copper; (e) nickel.

Moreover, Table 7 and Figure 11 show the thermal gradient in °C/mm of the honeycomb sandwich panel models with varying core materials.

Table 7. Measured total thermal gradient of models in °C/mm.

Core Material	Minimum Thermal Gradient	Maximum Thermal Gradient
Polystyrene (Control)	7.501E-09	0.019
Aluminum	1.759E-07	0.004
Nickel-Copper Alloy 400	1.776E-07	0.003
Copper	1.776E-07	0.003
Nickel	2.813E-07	0.007

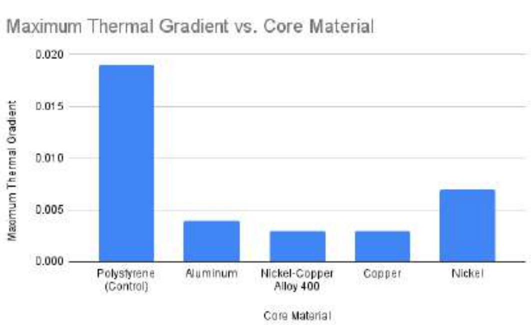

Figure 11. Measured maximum total thermal gradient of models.

As seen in Figure 11, the polystyrene honeycomb sandwich panel yielded the lowest minimum thermal gradient out of the other core materials. This is in line with its high specific heat and low thermal conductivity [3]. On the other hand, the panels with nickel-copper alloy 400 and copper as its core material yielded the lowest maximum thermal gradient out of the other core materials. These results show that the aforementioned core materials performed the best in terms of total thermal gradient since a lower thermal gradient indicates lower increases in temperature over distance.

Despite the polystyrene material being the most promising material overall in terms of heat resistance due to its relatively lower heat flux and thermal gradient, its high flammability and combustibility limit its applications as a core material for sandwich panels as these properties hinder its ability to be a fire-resistant option for construction [29].

4. Conclusion

This study has demonstrated the potential of honeycomb sandwich panels as a heat-resistant and durable construction material, specifically when incorporating various core materials such as aluminum, nickel-copper alloy, nickel, and copper. Through the utilization of finite element analysis, the study has revealed that the selection of core materials significantly impacts the structural and thermal performance of these panels.

The results suggest that the nickel-core honeycomb sandwich panels exhibited superior structural integrity, with the lowest static deformation and strain distribution. This suggests its ideal performance in applications requiring high durability under stress. Meanwhile, the polystyrene core showed the highest resistance to heat flux and thermal gradient, emphasizing its role as a thermally insulative material. However, its high flammability and combustibility limit its applicability in fire-resistance.

Amongst the metal-core honeycomb panels, the nickel-core sandwich panel yielded the highest resistance to the applied heat stressors, implying that it is the most promising metal for heat and fire-resistance applications.

While the study presents the feasibility of the different core honeycomb sandwich panels as a durable, and fire-resistant construction material, it also opens new avenues for exploring hybrid core materials and honeycomb structures. As such, future research could explore in flame simulations and investigate real-world testing to validate the simulation results.

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1. The study addresses a significant issue in urban construction—fire safety. With rising fire incidents, particularly in the Philippines, the focus on developing heat-resistant materials is timely and essential.

2. The discussion on the trade-offs between thermal resistance and flammability of materials (especially polystyrene) is insightful and highlights the complexity of material selection in construction.

3. Suggestions for this future research should focus on practical applications and further material testing to enhance the findings' applicability in real-world scenarios.