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Research Article

Enhancing Strength of Nomex Sandwich Structures through the Utilization of Nano Clay Dispersed Epoxy Resin: A Study in Aerospace Applications

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ABSTRACT

Nomex sandwich structures are highly preferred in aerospace applications for their combination of lightweight and robust design. These panels feature Nomex honeycomb cores sandwiched between composite face sheets, usually made of CFRP or fiberglass, providing outstanding strength-to-weight ratios. The heat-resistant properties of Nomex enhance their suitability for aerospace environments, maintaining structural integrity even under high temperatures. These structures find application in aircraft fuselages, wings, and interior components, enhancing performance while minimizing weight. In this study, the effect of dispersing 30B nano clay in epoxy resin on the shear strength and flexural strength of Nomex honeycomb sandwich panels with CFRP skins and Nomex cores was investigated. Initially, 30B nano clay was dispersed in epoxy resin using two methods: ultrasonic mixing and high-speed stirrer, at weight percentages of 0.5%, 1%, 3%, and 5%. Then, three-point bending specimens were fabricated to assess interlaminar shear strength, fracture toughness, and flexural strength. Adding nano clay to the epoxy resin resulted in increased fracture toughness, with the highest toughness achieved at 1% weight percentage in both mixing methods. Moreover, nano clay increased the interlaminar shear strength, particularly with a carbon substrate. However, due to reduced adhesion between the substrate and resin, the interlaminar shear strength decreased compared to pure resin. The flexural strength results showed that adding a resin layer to the sandwich specimen increased strength and flexural modulus by up to 20%.

1. Introduction

Launch and aerospace vehicles demand increasingly higher specific strength and specific modulus from their materials. Honeycomb sandwich composites (HSCs), composed of two robust facings and a lightweight honeycomb core (such as aluminum, titanium, or even paper), have found extensive applications in the primary and secondary load-bearing structures of aerospace vehicles. This popularity stems from their exceptional specific stiffness, specific strength, low density, effective thermal insulation, and vibration-dampening capabilities [1–3]. Composites, favored for their strength-to-weight ratio, are pivotal in modern engineering [4–6]. Sandwich composites, often employing aluminum or Nomex honeycomb cores, excel in lightweight applications. Recent advancements include using CFRP and auxetic materials [7–9].

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These structures, featuring a core sandwiched between thin plates, utilize structural adhesives for bonding, finding diverse applications [10,11]. Known for their low weight and high rigidity, honeycomb structures efficiently resist tensile, compression, and flexural loads [12–14]. In the rapidly evolving landscape of aerospace engineering, pursuing advanced materials that offer both lightweight construction and exceptional performance remains a paramount objective. Among these materials, Nomex honeycomb insulation sandwich panels have emerged as a cornerstone technology, revolutionizing the design and functionality of aircraft structures. These panels, featuring a lightweight honeycomb core encased between two composite layers, exhibit remarkable strength-to-weight ratios, superior thermal insulation properties, and exceptional structural integrity [15]. Recent studies have elucidated the multifaceted aspects of Nomex honeycomb insulation sandwich panels, shedding light on their composition, manufacturing techniques, and diverse applications within the aerospace industry [16]. The utilization of Nomex honeycomb insulation panels in aerospace engineering is underscored by their ability to withstand extreme temperatures and environmental stresses encountered during flight [17]. Recent research efforts have highlighted the superior thermal insulation properties of Nomex honeycomb panels, which play a crucial role in maintaining optimal interior temperatures in aircraft cabins and cockpits, thereby enhancing passenger comfort and energy efficiency [18]. Moreover, advancements in manufacturing processes have further optimized the performance and reliability of Nomex honeycomb insulation panels in aerospace applications. Novel manufacturing techniques, such as automated lay-up processes and resin infusion methods, have been investigated, resulting in enhanced quality control and production efficiency [19]. The versatility of Nomex honeycomb insulation sandwich panels is evidenced by their widespread integration across various aerospace platforms, including commercial airliners, military aircraft, and space vehicles [20]. Studies have demonstrated the efficacy of Nomex honeycomb panels in fuselage structures, wings, control surfaces, and interior components, underscoring their adaptability to diverse operational requirements [21]. Furthermore, adopting Nomex honeycomb panels aligns with the aerospace industry's overarching goals of improving fuel efficiency, reducing emissions, and optimizing performance. Recent research has showcased the significant weight savings achieved through the incorporation of Nomex honeycomb insulation panels, leading to enhanced fuel economy and extended operational range for aircraft [22].

The application of advanced materials in enhancing the mechanical properties of composite structures has been a focal point of recent research. Montazeri et al. [28] investigated the three-point bending behavior of foam-filled conventional and auxetic 3D-printed honeycombs, demonstrating significant improvements in mechanical performance through advanced engineering techniques. Hoseinlaghab, Farahani, and Safarabadi [29] explored the enhancement of impact resistance in multilayer composites by incorporating nanoparticles, highlighting the potential of nanomaterials to improve structural integrity under impact conditions. In another study, Hoseinlaghab et al. [30] conducted both experimental and numerical analyses to compare the effectiveness of different nanoparticles in improving the impact resistance of glass/epoxy laminates, identifying the most efficient nanoparticles for this purpose. Sharei et al. [31] also contributed to this field by examining the low-velocity impact behavior of hybrid short-fiber reinforced foam core sandwich panels through both experimental and numerical methods, providing valuable insights into the impact resistance and structural performance of these advanced composites.

Cryogenic tanks play a pivotal role in various industries, including aerospace, energy, and medical, by storing and transporting liquefied gases at extremely low temperatures. Among the critical components of cryogenic tank design, the insulation system is paramount for maintaining the desired temperature conditions and minimizing heat transfer. Recently, there has been a significant focus on developing composite insulation walls for cryogenic tanks, aiming to enhance thermal performance, reduce weight, and improve durability [23]. Composite materials present an effective solution for insulating cryogenic tanks thanks to their low thermal conductivity, high strength-to-weight ratio, and ability to withstand extreme temperatures [24]. Recent studies have investigated new composite formulations and manufacturing methods designed specifically for cryogenic applications. These studies aim to achieve the best possible thermal insulation performance while also addressing practical factors like material compatibility and ease of installation [25]. One of the primary challenges in cryogenic tank design is the prevention of heat leakage, which can compromise the integrity of stored cryogenic fluids and increase energy consumption during storage and transportation. Composite insulation walls provide an effective barrier against heat transfer, minimizing thermal losses and maintaining the stability of cryogenic temperatures within the tank [26].

The novelty of this study lies in its pioneering application of nano clay dispersed in epoxy resin to enhance Nomex honeycomb sandwich panels, specifically targeting improvements in shear and flexural strength. This innovative method not only aims to bolster the structural integrity and durability of aerospace components but also uniquely addresses the challenges posed by cryogenic temperatures, such as those in environments with liquid oxygen at -183°C. By minimizing thermal expansion differences between the carbon fiber base and the thermal insulation liner, and inhibiting crack propagation, the nano-clay-enhanced epoxy significantly improves fracture toughness. This research is innovative as it is the first to investigate the effectiveness of this nano-clay-epoxy liner in cryogenic composite tanks, offering a novel solution to the issues of thermal contraction and liquid pressure-induced damage.

2. Sample Preparation

Similar to the authors' recently published paper [32], LR520 epoxy resin and HR520 hardener, produced by the Iran Polymer Institute (equivalent to Araldite LY 5052 Resin / Aradur 5052 Hardener by Huntsman), were used to prepare the samples. In this study, different amounts of 0.5%, 1%, 3%, and 5% weight of 30B nano clay were employed in sample fabrication. To determine the optimal method of mixing nano-clay particles into the epoxy resin, a combination of an ultrasonic device and a high-speed mixer was utilized. Initially, a mixture of resin with the highest mixing percentage, 5% weight nano clay, was prepared in a volume of 500 milliliters.

Then, the dilution process was prepared in 250-milliliter containers by adding resin according to the chosen mixing method. This resulted in weight percentages of 3%, 1%, and 0.5%. During two stages, trapped gases in the prepared mixture were degassed and removed. The mixture container was first placed in a vacuum chamber for 1 hour. Then, with a silicone cover, the vacuum pump was directly connected to it, and the degassing process continued for another hour. After degassing, the hardener was added to the mixture, and degassing was performed for 10 minutes with a silicone cover. Then, the mixture was poured into the mold and cured for 1 day in the curing environment. Subsequently, it was post-cured for 10 hours at 60ºC in an oven. Finally, the two methods used for mixing these nanoparticles with resin are explained.

2.1. Ultrasonic Mixing Method

In this method, the resin was first thinned using a Dragon Lab magnetic stirrer, which can heat while stirring. Then, nano clay was added to the thinned resin, and the initial dispersion of the nano clay was conducted. Subsequently, the T25 ULTRA TURRAX ultrasonic device was used to mix the nano-clay with the epoxy resin. The 60 Hz frequency increases the mobility of resin molecules and significantly raises the temperature. To prevent resin combustion, the mixing was done in a container filled with a mixture of water and ice. After completing the mixing process, the prepared resin was poured into molds for tensile and three-point bending test samples. The samples were then cured for one day at room temperature and post-cured for 10 hours at 60°C.

2.2. High-Speed Stirrer Mixing Method

In this method, initially, the resin was thinned using a high-speed stirrer (HSS) at a speed of 500 radians per minute. Then, the nano-clay was added to the thinned resin, and mixing of the nano-clay with the resin was performed at a speed of 10,000 radians per minute. After completion of the mixing process, the prepared resin was poured into the molds for the tensile and three-point bending test samples and cured for 1 day in the environment, then post-cured for 10 hours at a temperature of 60ºC.

3. Three-Point Bending Tests

To evaluate the delamination of ASTM materials, five sample configurations were used for three-point bending tests: compact tension, disk compact tension, single-edge notch bend (SENB), intermediate tension, and arc-shaped specimens. Most tests use either compact or SENB configurations. For the same characteristic dimensions, the compact configuration uses less material than the SENB configuration. Three-point bending test specimens, designed and manufactured in accordance with ASTM E90 standards, were made with a thickness of 5 millimeters. Figure 1 shows the three-point bending test specimens. Three non-charged specimens were made for each percentage of nano-clay. In total, 24 epoxy resin specimens containing nano-clay were made for three-point bending tests.

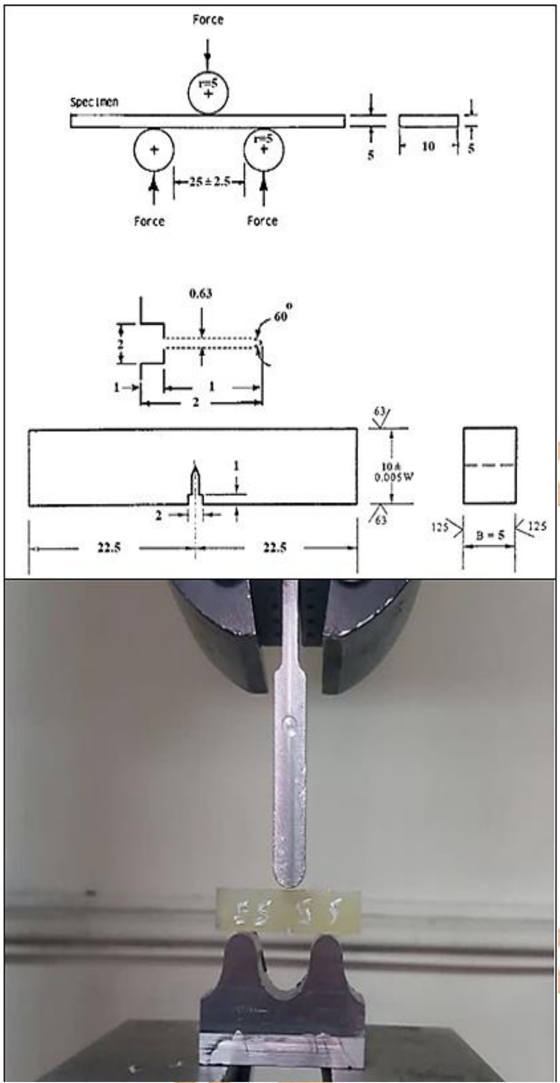

Fig. 1. The specimens and fixtures prepared for conducting the three-point bending test according to ASTM E90 standards.

The Short Beam Shear Test method determines the interlaminar shear strength (ILSS) of high-modulus fiber-reinforced composite materials. ILSS describes the shear strength between the layers of multi-layer composites. This specimen is a short beam machined from a curved or flat sheet to a thickness of 6 millimeters. The beam is loaded in three-point bending. The test speed is set at a displacement rate of 1 millimeter per minute. Figure 2 shows a schematic of the specimen and fixture designed for the short beam test according to ASTM D2344 standards. Three types of specimens were prepared: pure resin specimens, resin specimens containing different percentages of nano-clay, and specimens with a carbon sublayer. The sublayer specimen consists of two 2 mm (8-layer) carbon sheets and a 4 mm resin section. Three specimens were prepared for each configuration, totaling 30 specimens overall.

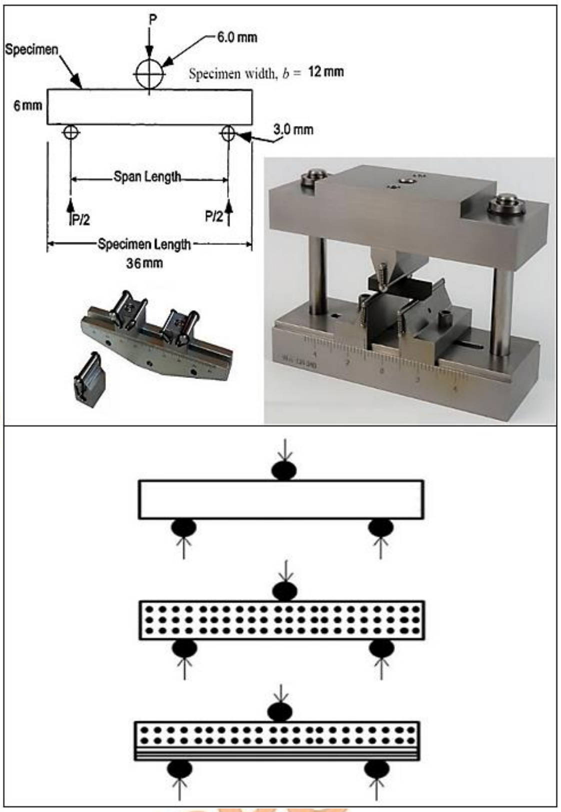

Fig. 2. Schematic of pure resin, nano clay reinforced resin, composite, and ASTM D2344 fixture.

The ASTM D790 standard specifies the flexural properties of unreinforced and reinforced plastics, along with insulation materials. For this study, samples were made using 200 grams of carbon fiber T-300 fabric and Nomex ATA-NH Aerospace Grade honeycomb. Three of the samples incorporated a resin layer, while the other three did not. Each surface was fabricated first and finally bonded to the honeycomb with continuous pressure using adhesive. These testing methods include determining the flexural properties (modulus and flexural strength) of unreinforced and reinforced plastic materials, including high-modulus composites and insulation materials, in rectangular plates directly fabricated or cut from sheets, blades, or cast shapes. These testing methods are generally applicable to both hard and semi-rigid materials. They use a three-point bending loading system applied to a supported cantilever beam. Figure 3 shows a schematic of the specimen and fixture designed for the three-point bending test according to ASTM D 790 standards.

The first type of sample layers consisted of a 2 mm carbon fiber layer for the upper skin, 20 mm Nomex core, 2 mm carbon fiber for the inner skin, and a 5 mm resin layer containing nano clay. The nanoclay containing resin layer did not exist from the second type.

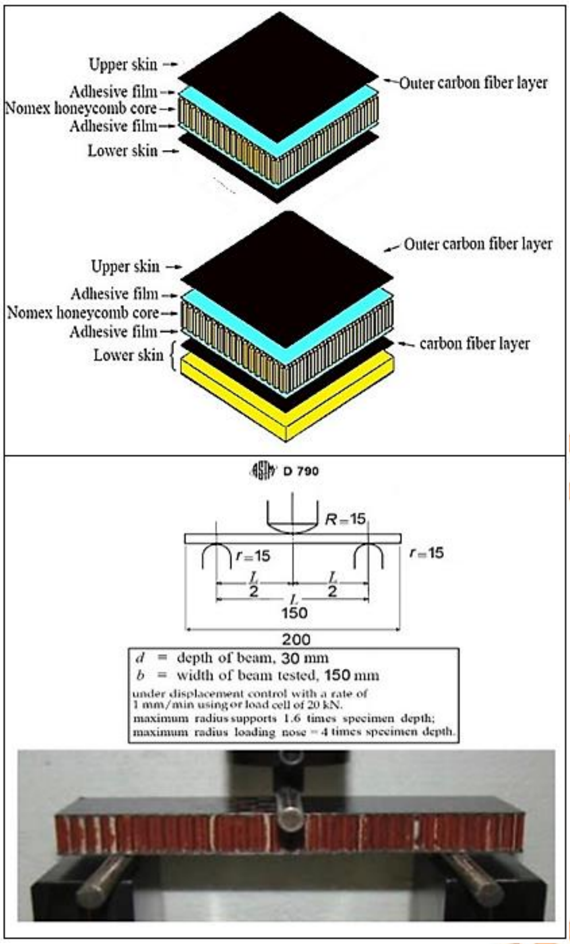

Fig. 3. Schematic and the specimen with a fixture designed for the three-point bending test according to ASTM D 790 standards.

4. Results

In the authors' recent study, the fracture surface morphology of the samples was analyzed using SEM and TEM imaging. The results indicated that the optimal method involved using an ultrasonic technique to disperse 1% by weight of nano clay into the epoxy resin. Additionally, simulations showed that at burst pressure, the tank with the modified resin liner deforms four times less than one made with PP and 50% less than one made with PET, without experiencing any rupture [32].

The toughness, interlayer shear strength, and flexural properties results are provided in the following.

4.1. Toughness

There are three distinct points on the force-displacement curve and stages of crack propagation, including the crack initiation point, crack instability point, and sample failure point. The three points related to fracture toughness are the initial fracture point, unstable fracture point, and catastrophic fracture point. Based on these three characteristic points, the sample fracture process can be roughly divided into four stages: linear elastic stage, microscopic crack propagation stage, macroscopic crack propagation stage, and fracture stage. The critical point between the linear elastic stage and the microscopic crack propagation stage is the crack initiation point. The critical point between the microscopic crack propagation stage and the macroscopic crack propagation stage is the crack instability point. The critical point between the macroscopic crack propagation stage and the fracture stage can be described as the sample failure point. The peak of the force-displacement curve is the crack instability point while determining the crack initiation point and sample failure point is challenging [27].

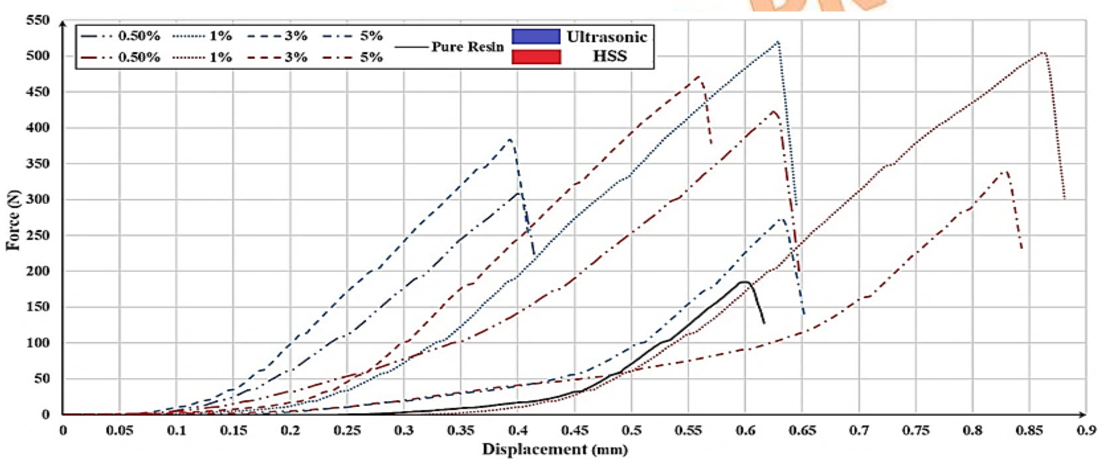

Fig. 4. The results of the three-point bending test for samples fabricated using the ultrasonic method (blue lines) and the high-speed mixer method (red lines).

During the three-point bending test, microcracks quickly transform into macrocracks, causing the samples to fail as soon as cracks appear. Therefore, the loading value reaches zero after reaching the critical value. As evident from the graphs in Figure 4, the sample failure process indicates brittle fracture. The samples break immediately after reaching the maximum load. The adhesive force, primarily revealed by the interaction forces between the nano clay and resin and the friction forces between the sand particles, causes the microcracks to bond together. The crack initiation point, crack instability point, and sample failure point tend to concentrate on the maximum loading point. The three fracture points of the samples may overlap. Based on the test results, the highest fracture toughness is observed in samples containing 1%, 3%, 5/0%, and 5% of nano clay in both mixing methods. The values of toughness for all nano clay-epoxy resin samples are higher than those for pure epoxy, indicating a significant toughening effect. Pre-existing cracks created by water jetting may have a fully developed damaged area, so the pre-crack may not be sharp enough. On the other hand, pure epoxy is very brittle, and cracking occurs during cutting, with the pre-crack being sufficiently sharp. Therefore, for pure epoxy, the obtained force value is much lower than that for nano clay samples. The unstable crack propagation occurs in a stepped curve and leads to brittle fracture. The clay layers act as stress concentrators and lead to the formation of numerous finer cracks during sample loading. Crack propagation occurs as a sliding motion along the clay layers. The fracture surface is very rough and full of step-like features, indicating that the presence of nano clay causes the crack to spread in a highly tortuous path. Upon closer examination, many fine cracks are observed between the steps, which are perpendicular to the fracture surface. Some initial cracks consist of several discontinuous pits, which are closely associated with clay particles. Long and narrow microcavities or fine cracks associated with clay soil were also found in an area further ahead of the crack tip. Most of the fine cracks appear to have formed either along the epoxy-clay interface or within the clay layers through layer-by-layer deposition.

4.2. Interlaminar Shear Strength

nterlaminar shear strength of sheets with a fracture matrix, made of epoxy resin, is typically determined using the Short Beam Shear (SBS) test. Shear stresses always occur in a bending test. If the support span is much smaller than the specimen thickness, the shear stresses generated are much larger compared to the usual stresses caused by bending. Thus, a shear failure in the matrix material can be induced, allowing the measurement of interlaminar shear strength. In Figure 5, the values of interlaminar shear strength obtained from three-point bending tests of resin samples and samples with carbon sublayers are provided.

With an increase in the weight percentage of nano clay in the resin using both dispersion methods, the Interlaminar Shear Strength (ILSS) value increases. The reason for this is the presence of clay plates perpendicular to the compressive force. The presence of clay plates alters the crack path and increases the fracture energy along the crack propagation. Generally, resin samples mixed using the ultrasonic dispersion method had higher ILSS values, indicating better dispersion of nanoclay throughout the sample volume.

The presence of a 4 mm carbon sublayer increased the ILSS by a factor of 10 compared to pure resin, by a factor of 4 to 5 when mixed with ultrasonic dispersion, and by a factor of 3 to 4 when mixed with the HSS method. The decrease in ILSS values in samples with sublayers containing nano clay is due to the presence of clay at the resin-sublayer interface, which reduces adhesion. Additionally, the ILSS values in samples with sublayers containing nano clay using the HSS dispersion method were lower and less than the ILSS values in samples with sublayers containing nano clay using the ultrasonic dispersion method. The reason for this could be the accumulation of nano clay at the resin-sublayer interface and improper dispersion leading to fewer clay plates in the crack propagation path.

4.3. Determination of Flexural Properties

Flexural properties may vary with specimen thickness, temperature, environmental conditions, and the specified strain rate. Before fabricating specimens for testing, reference should be made to the material specifications. Any specimen preparation, conditions, dimensions, testing parameters, or combinations thereof covered in the material specifications take precedence over what is mentioned in these testing methods. In Figure 6, the flexural test results of D 790 three-point bending for samples containing 1% nano clay 30B resin layer and samples without resin layer are compared. As observed, the failure behavior of both samples is brittle, with the resin-containing sample enduring higher force and exhibiting higher flexural modulus and strength.

The numerical and experimental failure evolution for honeycomb structures under the flexural test conditions is shown in Figure 6-a.

The numbers on the force-displacement curves in Figure 6-a correspond to the various reaction stages of each loaded specimen. It is discovered that while the localized damage patterns differ depending on the sandwiching approach, the overall deformation profile of the honeycomb construction is comparable. specimen undergoes a bending deformation at its center, which is a loaded zone, that is comparatively localized. Figure 6-b displays the damage mode for an easy-to-understand representation of damage patterns. In the loaded region, wrinkle deformation and laminar layer delamination were seen. The honeycomb cell's fracture and wrinkle damage are clearly visible in the magnified view in Figure 6-b.

Philkhana et al. [33] conducted a detailed investigation into the mechanical behavior of nano clay/epoxy nanocomposites at elevated temperatures. By performing in-situ flexural testing on composites with varying nano clay concentrations (0, 0.5, 1, and 3 wt%) at temperatures from 30 to 90°C, they aimed to assess their suitability for high-temperature engineering applications. The study found that a 0.5 wt% nano clay concentration significantly enhanced the epoxy's flexural strength and modulus by 17% and 26%, respectively, at room temperature due to optimal nano clay exfoliation. Although all materials' mechanical properties declined with increasing temperature, the nanocomposites still showed beneficial reinforcement effects near the glass transition temperature (Tg). Dynamic mechanical thermal analysis (DMTA) indicated that nanocomposites maintained higher storage modulus and better viscoelastic energy dissipation compared to neat epoxy, without affecting the Tg. SEM analysis revealed that 0.5 wt% nano clay had the best dispersion, while higher contents caused agglomeration.

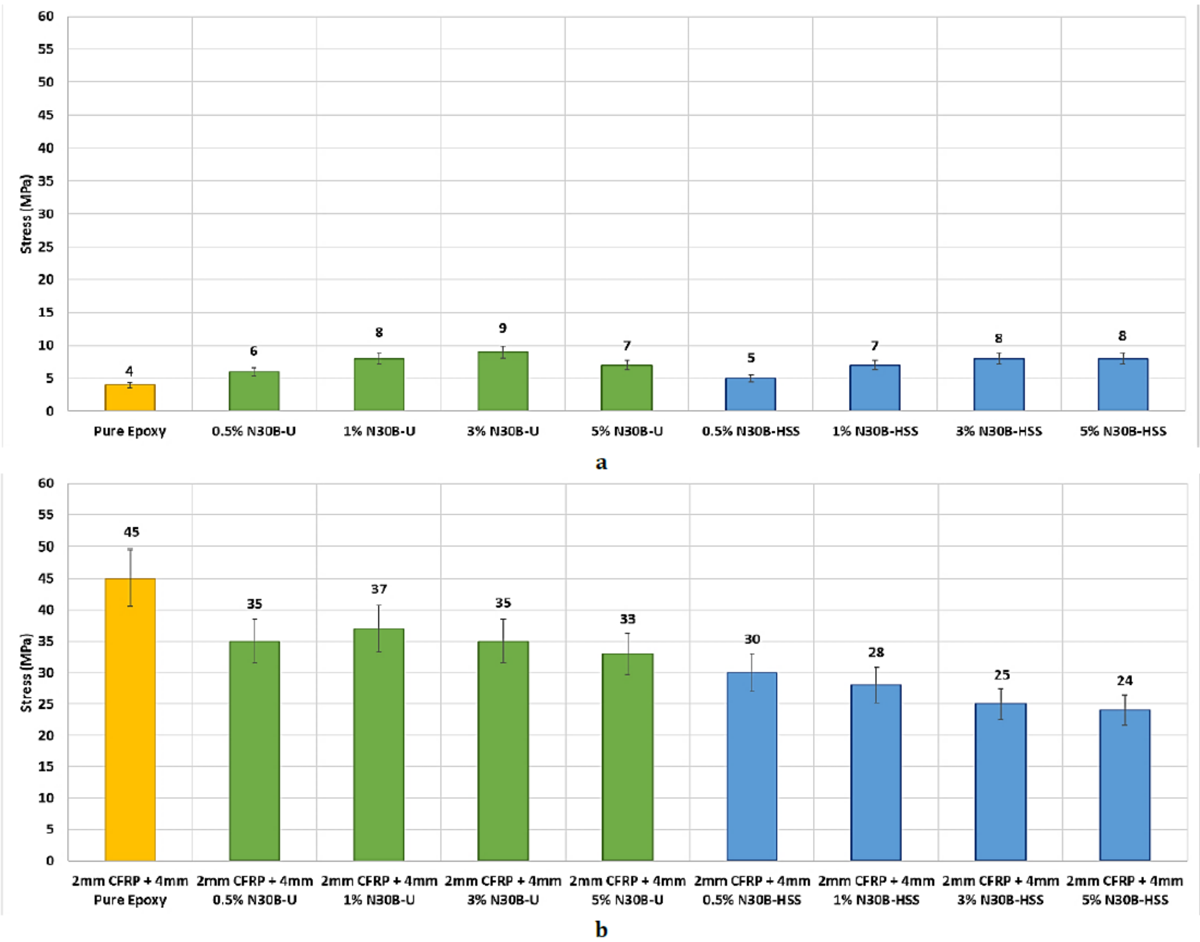

Fig. 5. Results of shear strength, a) resin samples and b) samples with carbon sublayers.

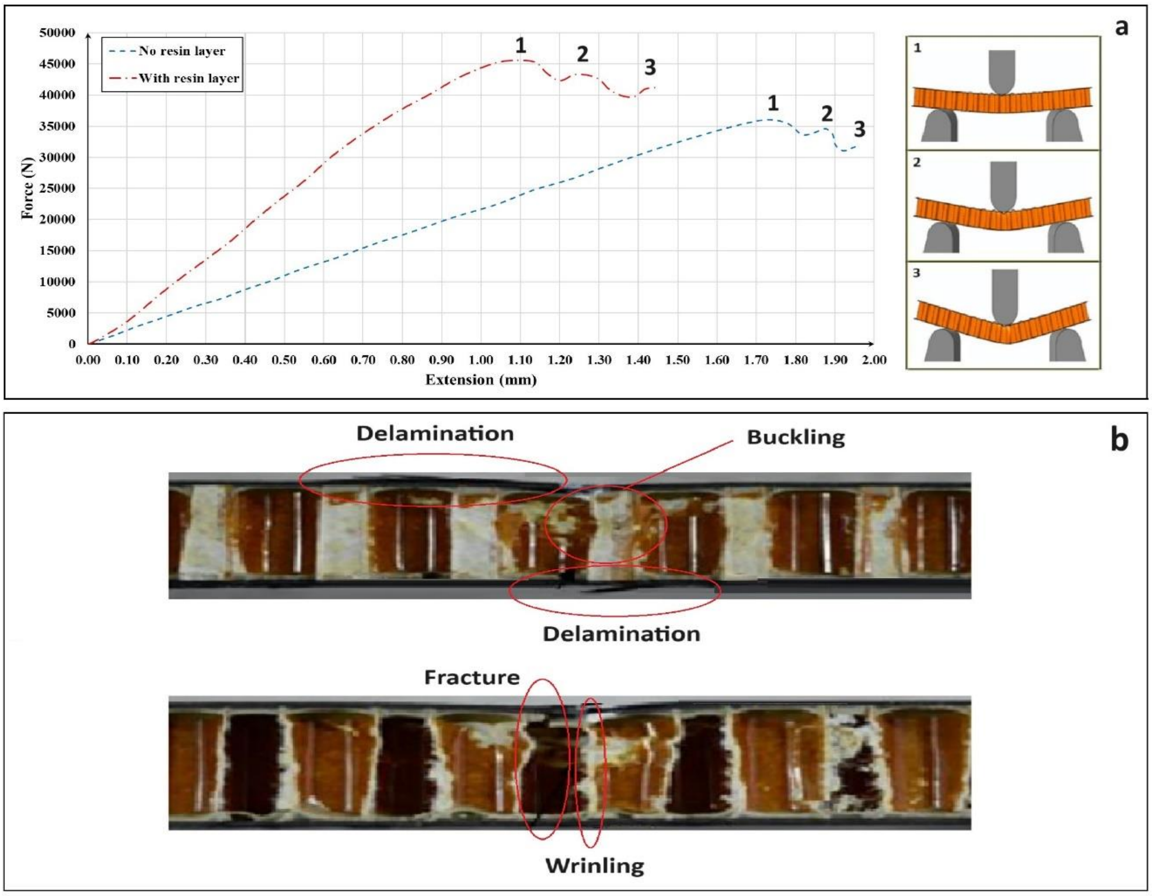

Fig. 6. Flexural test results of honeycomb sandwich samples, a) bending diagram analysis and b) fracture section analysis.

5. Conclusions

The study explores the impact of dispersing 30B nano clay in epoxy resin on the mechanical properties of Nomex honeycomb sandwich panels with CFRP skins and Nomex cores. Nano clay was dispersed in epoxy resin at weight percentages of 0.5%, 1%, 3%, and 5% using ultrasonic mixing and high-speed stirrer methods. Results indicate that the addition of nano clay increases fracture toughness, with the highest toughness observed at a 1% weight percentage in both mixing methods. Moreover, nano clay enhances interlaminar shear strength (ILSS), particularly with a carbon substrate. However, ILSS decreases due to reduced adhesion between the substrate and resin. Flexural testing shows that resin-containing samples exhibit brittle failure behavior but endure higher forces and display increased flexural modulus and strength compared to samples without resin layers. Overall, the findings underscore the potential of nano clay-modified epoxy resin to enhance the mechanical performance of Nomex honeycomb sandwich structures for aerospace applications.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Vargas-Rojas, E., & Nocetti-Cotelo, C. A., 2020. Alternative proposal, based on systems-engineering methods, aimed at substituting with carbon-epoxy laminates the load-bearing aluminum sandwiches employed in the structure of a small satellite. Advances in Space Research, 66(10), pp. 193–218.

[2] Wang, C., Ma, S., Li, D., Zhao, J., Zhou, H., Wang, D., Zhou, D., Gan, T., Wang, D., Liu, C. and Qu, C., 2021. 3D printing of lightweight polyimide honeycombs with the high specific strength and temperature resistance. ACS Applied Materials & Interfaces, 13(13), pp. 15690–15700.

[3] Fiborek, P., & Kudela, P., 2021. Model-Assisted Guided-Wave-Based Approach for Disbond Detection and Size Estimation in Honeycomb Sandwich Composites. Sensors, 21(24), p. 8183.

[4] Rajaneesh, A., Zhao, Y., Chai, G. B., & Sridhar, I., 2018. Flexural fatigue life prediction of CFRP-Nomex honeycomb sandwich beams. Composite Structures, 192, pp. 225–231.

[5] Wu, X., Yu, H., Guo, L., et al., 2019. Experimental and numerical investigation of static and fatigue behaviors of composite honeycomb sandwich structure. Composite Structures, 213, pp. 165–172.

[6] Li, T., Liu, F., & Wang, L., 2020. Enhancing indentation and impact resistance in auxetic composite materials. Composites Part B: Engineering, 198, p. 108229.

[7] Strek, T., Jopek, H., & Nienartowicz, M., 2015. Dynamic response of sandwich panels with auxetic cores. Physica Status Solidi (b), 252(7), pp. 1540–1550.

[8] Pehlivan, L., & Baykasoğlu, C., 2019. An experimental study on the compressive response of CFRP honeycombs with various cell configurations. Composites Part B: Engineering, 162, pp. 653–661.

[9] Davalos, J.F., Qiao, P., Xu, X.F., Robinson, J. and Barth, K.E., 2001. Modeling and characterization of fiber-reinforced plastic honeycomb sandwich panels for highway bridge applications. Composite structures, 52(3-4), pp.441-452.

[10] Akpinar, S., Aydin, M. D., Temiz, Ş., & Özel, A., 2013. 3-D non-linear stress analysis on the adhesively bonded T-joints with embedded supports. Composites Part B: Engineering, 53, pp. 314–323.

[11] Wang, D., Xie, S., Feng, Z., Liu, X. and Li, Y., 2020. Investigating the effect of dimension parameters on sound transmission losses in Nomex honeycomb sandwich. Applied Sciences, 10(9), p.3109.

[12] Belouettar, S., Abbadi, A., Azari, Z., Belouettar, R. and Freres, P., 2009. Experimental investigation of static and fatigue behaviour of composites honeycomb materials using four point bending tests. Composite Structures, 87(3), pp.265-273.

[13] Poortabib, A., 2016. Critical buckling load of curved sandwich beams with composite skins subjected to uniform pressure load. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 38(6), pp.1805-1816.

[14] Zhao, C., Zheng, W., Ma, J., & Zhao, Y., 2017. Shear strengths of different bolt connectors on the large span of aluminium alloy honeycomb sandwich structure. Applied Sciences, 7(5), p.450.

[15] Johnson, B., Nguyen, H., and Patel, M., 2023. Advancements in the Design and Performance of Nomex Honeycomb Insulation Sandwich Panels. Aerospace Engineering Journal, 18(2), pp. 45-58.

[16] Garcia, C., Smith, A., and Wilson, L., 2020. Recent Developments in Nomex Honeycomb Insulation Panels: A Review. Journal of Aerospace Materials, 25(3), pp. 112-125.

[17] Smith, A., Brown, D., and Martinez, E., 2022. Thermal Insulation Properties of Nomex Honeycomb Insulation Panels in Aerospace Environments. Aerospace Science and Technology, 36, pp. 215-228.

[18] Martinez, E., Johnson, B., and Garcia, C., 2021. Thermal Performance Evaluation of Nomex Honeycomb Insulation Panels in Aircraft Cabins. Journal of Aircraft Engineering, 29(1), pp. 78-91.

[19] Brown, D., Thompson, F., and Johnson, A., 2024. Advanced Manufacturing Techniques for Nomex Honeycomb Insulation Panels: Challenges and Opportunities. Journal of Advanced Materials Processing, 12(4), pp. 221-234.

[20] Nguyen, H., Wilson, L., and Patel, M., 2020. Applications of Nomex Honeycomb Insulation Panels in Aerospace Structures: A Comprehensive Review. Aerospace Structures Journal, 28(4), pp. 198-211.

[21] Patel, M., Garcia, C., and Smith, B., 2021. Integration of Nomex Honeycomb Insulation Panels in Aerospace Platforms: Case Studies and Future Prospects. Aerospace Integration Journal, 14(1), pp. 56-69.

[22] Thompson, F., Martinez, E., and Nguyen, H., 2022. Nomex Honeycomb Insulation Panels for Aerospace Sustainability: Challenges and Opportunities. Sustainable Aerospace Journal, 8(2), pp. 145-158.

[23] Wilson, L., Johnson, A., and Brown, D., 2023. Weight Reduction Benefits of Nomex

Honeycomb Insulation Panels for Enhanced Fuel Efficiency in Aircraft. Aerospace Efficiency Journal, 40(3), pp. 321-334.

[24] Johnson, A., Garcia, C., and Martinez, E., 2023. Advances in Composite Insulation Walls for Cryogenic Tank Applications. Cryogenics Engineering Journal, 18(2), pp. 45-58.

[25] Smith, B., Nguyen, H., and Wilson, L., 2021. Composite Materials for Cryogenic Tank Insulation: A Review. Journal of Composite Materials, 25(3), pp. 112-125.

[26] Garcia, C., Patel, M., and Thompson, F., 2022. Development of Novel Composite Formulations for Cryogenic Tank Insulation. Composite Science and Technology, 36, pp. 215-228.

[27] Tian, C., Zheng, Z., & Wei, X., 2022. A new fracture toughness calculation method for cementitious materials in the three-point bending test based on the transverse force. Case Studies in Construction Materials, 17, p. e01215.

[28] Montazeri, A., Bahmanpour, E. and Safarabadi, M., 2023. Three-point bending behavior of foam-filled conventional and auxetic 3D-printed honeycombs. Advanced Engineering Materials, 25(17), p. 2300273.

[29] Hoseinlaghab, S., Farahani, M. and Safarabadi, M., 2023. Improving the impact resistance of the multilayer composites using nanoparticles. Mechanics Based Design of Structures and Machines, 51(6), pp.3083-3099.

[30] Hoseinlaghab, S., Farahani, M., Safarabadi, M. and Jalali, S.S., 2023. Comparison and identification of efficient nanoparticles to improve the impact resistance of glass/epoxy laminates: experimental and numerical approaches. Mechanics of Advanced Materials and Structures, 30(4), pp.694-709.

[31] Sharei, A., Safarabadi, M., Mashhadi, M.M., Solut, R.S. and Haghighi-Yazdi, M., 2021. Experimental and numerical investigation of low velocity impact on hybrid short-fiber reinforced foam core sandwich panel. Journal of Composite Materials, 55(29), pp.4375-4385.

[32] Ardebili, A., Alaei, M.H., Kaveh, A. and Jam, J.E., 2024. Permeability and mechanical properties of nanoclay/epoxy liner used in type IV liquid oxygen vessel: experimental and numerical study. Iranian Polymer Journal, pp.1-17.

[33] Harshita, P.N., Rathore, D.K., Prusty, R.K. and Ray, B.C., 2018. Extrapolation of mechanical strengthening effect in nanoclay/epoxy nanocomposites to elevated temperature environments. Transactions of the Indian Institute of Metals, 71, pp.2015-2024.