Research Article

Journal of
Environmental
Nanotechnology

Integration of Nanotechnology in Honeycomb Composites for Sustainable Structural Solutions

B. S. Gnana Betsy and N. Umamaheswari*
Department of Civil Engineering, SRM Institute of Science and Technology, Kattankulathur, TN, India
Received: 18.12.2024 Accepted: 25.01.2025 Published: 30.03.2025
*umamahen@srmist.edu.in

ABSTRACT

Composite construction has become a basis of modern infrastructure, since it offers faster, cost-effective, and attractive solutions. Among these, honeycomb structures, nature-inspired geometric designs are widely recognized for their superior energy absorption, lightweight, and high strength-to-weight ratio. They are used in diverse fields, such as protective energy-absorbing systems, automotive frameworks, aerospace substructures, and advanced engineering solutions. The integration of nanotechnology into honeycomb composites marks a transformative opportunity for sustainable structural development. Nanomaterials, such as carbon nanotubes, graphene, and nanosilica, can significantly enhance the mechanical, thermal, and environmental performance of honeycomb composites by improving their strength, durability, and resistance to external stresses. The present study identifies critical research gaps in the intersection of honeycomb composites and nanotechnology. It explores the potential of nano-enhanced honeycomb materials to address challenges in sustainable construction, such as resource efficiency, energy optimization, and long-term environmental impacts. By enhancing the unique properties of nanomaterials, honeycomb composites can offer next-generation solutions for structural systems that are not only stronger, lighter, and cost-efficient but also environmentally sustainable. This study also outlines future research directions for integrating nanotechnology in honeycomb composite construction, with an emphasis on eco-friendly materials, lifecycle performance, and innovative applications in the fabrication. The findings emphasize the need for multidisciplinary approaches to advance composite construction techniques, ultimately paving the way for a resilient and sustainable infrastructure framework.

Keywords: Nanocomposites; Honeycomb structures; Sustainable construction; Structural performance

1. INTRODUCTION

Composites are multiphase material systems, and their behavior depends on the constituents. Practically every element of human life has been impacted by the development of advanced composites, and now considerable effects are being seen in the civil engineering, sports goods, aerospace and aviation, automotive, and sporting goods industries. High tensile strength, stiffness, fatigue strength, design flexibility, reduced corrosion, etc. are only a few of the key benefits of employing composite materials (Buragohain and Manoj, 2017), There is always an interface between the two or more constituents that make up composite material. A face sheet is placed on the top and bottom sides of a sandwich composite containing a honeycomb material. A few examples of composite materials include glass, carbon (high strength), aramid or kevlar (both very light), etc. Most matrix materials are composed of metal matrices, mineral matrices (silicon carbide, carbon), and polymer matrices (thermoplastic and thermosetting resins) (Aluminum alloys, titanium alloys, and oriented eutectics) as per work described by (Anil *et al.* 2020).

Beehives and weathered honeycombs in rocks are only two examples of the various places where natural honeycomb formations may be found. Based on this, manufactured honeycomb structures with similar form were designed to use less material, become lighter, and economical to produce. Hollow cells sandwiched between thin vertical walls can be used to create artificial honeycomb structures that have high tensile strength, low density, and good hybrid capabilities (Shilong *et al.* 2020). In several industries, including the automotive and aerospace sectors, composites have been employed for a longer period within structures. But nowadays, reinforcing plates or rods with components (fibre or resin) theoretically enable tailoring design approaches to produce economical hybrid material to fit its environment, and achieve performances superior to conventional models (Bigaud and Hamelin, 2002). In this paper, the overview of a honeycomb composite was explained in detail for the future investigation of works and to enhance research work based on geometry of honeycombs in both structural and non-structural aspects.

1.1 Honeycomb Structure and Honeycomb Composites

Since ancient times, people have appreciated the hexagonal crest of the honeybee. Greek mythology claims that Daedalus created the first artificial honeycomb more than three thousand years ago using a lost wax casting method and gold. According to Marcus Varro, Greek mathematicians Euclid and Zeno Dorus discovered that the hexagonal design best uses both space and building resources. An early illustration of a honeycomb construction may be seen in the inner ribs and secret chambers of the dome of the Pantheon in Rome (Diodorus). According to G.P. Thomas, the hexagonal pattern of the natural honeycomb used by the insects to create the hive was first seen in olden times. Marcus Varro is credited with having recognized hexagons as a very effective use of space and building resources in the year 36 BC. The dome of the Pantheon, in Rome, was rejuvenated and supported by a framework that resembled a stacked hexagonal form. This offered additional strength and stability of the design to the structure. The honeycomb structure design has been in use since the 1980s. Extremely low density and great strength were achieved on a wide scale with thermoplastic extruded honeycombs. The uses for honeycombs are virtually endless. Aluminum wall coverings with a honeycomb design are sometimes used in contemporary structures for strength and beauty. In some circumstances, honeycomb-based insulation is also employed to create compact and reliable structures (Thomas, 2013).

2. MATERIALS AND METHODS

2.1 Manufacture of Honeycomb Composites

Three established techniques expansion, corrugation, and molding have been used to create honeycomb structures since the early 1900s. Today, composite materials like fibreglass, aluminum, and carbon fibre-reinforced plastic are employed in expansion and corrugation processes to create honeycomb cores. For the creation of thermoplastic honeycomb structures, a more recent cost-effective method enables direct skin lamination and continuous line production. Similarly, metal honeycomb may also be continually created by cutting and bending metal rollers. In addition to metal composite honeycomb structures, cardboard honeycomb materials are also made for usage in blocking paper containers and pallets, bracing, and cushioning the outside of composite constructions (Thomas, 2013). Honeycomb offers a special framework made of a wide range of materials, including thermoplastics, cement, fiberglass, aluminum, and steel.

The main advantages of honeycomb composites are their outstanding weight-to-strength ratio, corrosion protection, elevated resilience, fire resistance, temperature-withstanding capability, and moisture resistance, and simple to fabricate and mold. Additionally, the honeycomb composites are easily portable, less susceptible to bending, good in shock and vibration absorbance, and resistance to rust, water, microorganisms, acids, and bases (Thomas, 2013). The composite honeycomb structures have been used in various engineering and scientific applications such as skateboards and skis, jet planes and rocket structures, both LED and loudspeaker technologies, automobile structures, light, enclosures that safeguard electricity, windmill blades, exterior architectural curtain walls and clean room panels, equipment and gadgets for heating, ventilation, and air conditioning, and energy-absorbing defense mechanisms. For the sandwich construction, the honeycomb is sandwiched between two thin material panels, which is the most typical application using honeycomb as the core of composites. This sandwich design successfully combines the lightweight and high-strength properties of the honeycomb, which is essential for the aerospace sector, with the smooth, flat surfaces of the panels to facilitate installation (Thomas, 2013).

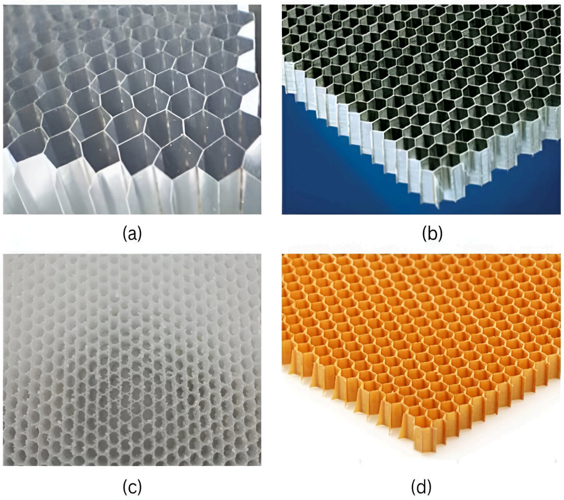


Fig. 1: Types of honeycombs of (a) Aluminum (b) Stainless steel (c) Thermoplastic (d) Nomex

2.2 Types of Honeycomb Composites

2.2.1 Aluminum Honeycombs

The dimensions of the units as well as the thicknesses of the foil define the properties of aluminum honeycombs, which have the maximum strength-to-weight ratio and a wide range of geometric cell arrangements. Aluminum honeycombs are susceptible to corrosion when employed in maritime constructions and permanently distort when they come into contact with cored laminates. Aluminum honeycombs are frequently employed in situations where weight is an issue, therefore enhancing their strength and capacity for energy absorption is crucial. An innovative tube-reinforced honeycomb structure comprised of thin-walled metallic tubes was used to enhance the mechanical characteristics of aluminum honeycomb. Fig. 1(a) of the Aluminum honeycomb shown above was taken from.

The benefits of aluminum honeycombs are they weigh just 1/3 as much as steel. They are strong, corrosion resistant, good conductors of heat and electricity, and are completely recyclable without losing their organic properties. Aluminum honeycombs are simple to construct, mold, and shape. At 650 °C, aluminum begins to melt and does not burn. They are stronger than steel when paired with another metal, such as silicon or magnesium. An aluminum honeycomb is utilized in various applications such as rail in furniture, walls, flooring, hygienic units, radiation absorbers, doors, and partition panels, hulls and compartments, furnishings, ceilings, and floor paneling, inside panels and partitions, and doors are all included within the marine category, upholstery, operating rooms, roof, and floor slabs, and building facades each serve a value in construction, industrial applications for trial mattresses, stream smoothing (air and liquid), ventilating and air conditioning, immunity to electromagnetic interference, and external sculptural screen wall panels (laser and waterjet), and automotive sector for armored trucks, impact force relievers, wind generators, propellers, turbo cladding, mold construction, etc.

2.2.2 Nomex Honeycombs

Nomex honeycombs are manufactured with nomex paper and Kevlar fibres. They have excellent strength and fire-resistance qualities and are more expensive. Nomex Honeycomb is a non-metallic core material with a typical hexangular cell structure that is lightweight, high strength, and produced from aramid fibre paper. A heat-resistant phenolic resin is applied to increase the strength and thermal capacity. They have a high strength-to-weight ratio, stiffness, and binding property. Nomex Honeycomb is used more often in high-performance, non-aerospace products because of its superior mechanical qualities, low density, and long-term stability, and in building that needs corrosion resistance and thermal insulation. Fig. 1(d) of the Nomex honeycomb shown above was taken from Easy Composites Ltd website.

The Nomex honeycomb has excellent weight-to-strength ratio, simple shape-changing property, outstanding self-extinguishing and fire-resistant qualities to FAR 25.583, corrosion resistance when exposed to water, oil, and gasoline, temperature resistance (maximum service temperature is 356 °F), strong dielectric characteristics, and molded to specified thickness. The Nomex honeycomb structure is used in leading and trailing edges of aircraft. ailerons, sidewalls, galleys, seats, floors, and ceilings for aircraft, safety features on race vehicles, barrier crash tests, rail components (doors, floors, and ceilings), and composite hulls, panels for naval bulkheads, military refuges, skates and snowboards, shells for racing, energy-absorbing barriers for protection, and radar and communications sectors (antennas and radomes).

2.2.3 Thermoplastic Honeycombs

Thermoplastic Honeycomb Core is a cutting-edge architectural material inspired by the natural structure of honeycombs, comprised of polypropylene (PP), polycarbonate (PC), or polyethylene terephthalate (PET). This innovative material boasts exceptional properties, including lightweight construction, high compressive strength, eco-friendliness, water and moisture resistance, and corrosion resistance. Offering numerous advantages, such as being eco-friendly and recyclable, resistant to moisture, water, and corrosion, and providing excellent sound insulation and energy absorption properties, Thermoplastic Honeycomb Core is widely used in various industries, including automotive, packaging, advertising, building sector, and aerospace and railroad industries, enabling the creation of innovative and eco-friendly products. (Gadkaree, 1998). Fig 1(c) shown above was taken from Trusmax composites team.

2.2.4 Stainless-steel Honeycombs

The stainless-steel honeycomb core is used in floors, bulkheads, train doors, and joiner panels. Fig 1(b) stainless steel honeycomb shown above was from the reference. The stainless-steel honeycombs have excellent resistance to dampness and rusting, high thermal stability, and fungi militancy. The applications of stainless-steel honeycombs are air, water and gas flow straighteners and filters, EMI/RF Shielding, tables for water jets, structural honeycomb for aircraft, thrust reversers, exhaust nozzles, and aircraft engine honeycomb seals (honeycomb cores and panels).

2.3 Honeycomb Structures

2.3.1 Honeycomb Core Structures

Instruments that are simple to construct and extrude the hexagonal cell structure were used in the preliminary design study. Then, an assembly of a collection of hexagonal cells was made for several research instances. In secondary level the rectangular panel design was used, and computer programs the internal ballistics, fluid dynamics, and continuum mechanics. For the structural analysis to describe physical processes in 1D, 2D, and 3D, finite difference or finite element techniques were used. (Shaik *et al.* 2015) enabled precise calculations or optimization to obtain a desired final form and is shown in Fig. 2.

2.3.2 Honeycomb Sandwich Panel Construction

Sandwich constructions are widely used for applications where high flexural stiffness and strength are required. To control the weight of the sandwich panel, the face sheets are typically built using continual fiber-reinforced polymers or metals that also offer significant rigidity and strength. The core of the sandwich panel is constructed with honeycomb, foam, perforated plate, and truss. By inserting a core between the skins, the moment of inertia increases, enhancing rigidity and reducing stress. The unique mechanical and physical characteristics of each core structure make them appropriate for a variety of functions (Anil *et al.* 2018).

2.3.3 Unit Cells and Densities of Honeycomb Structures

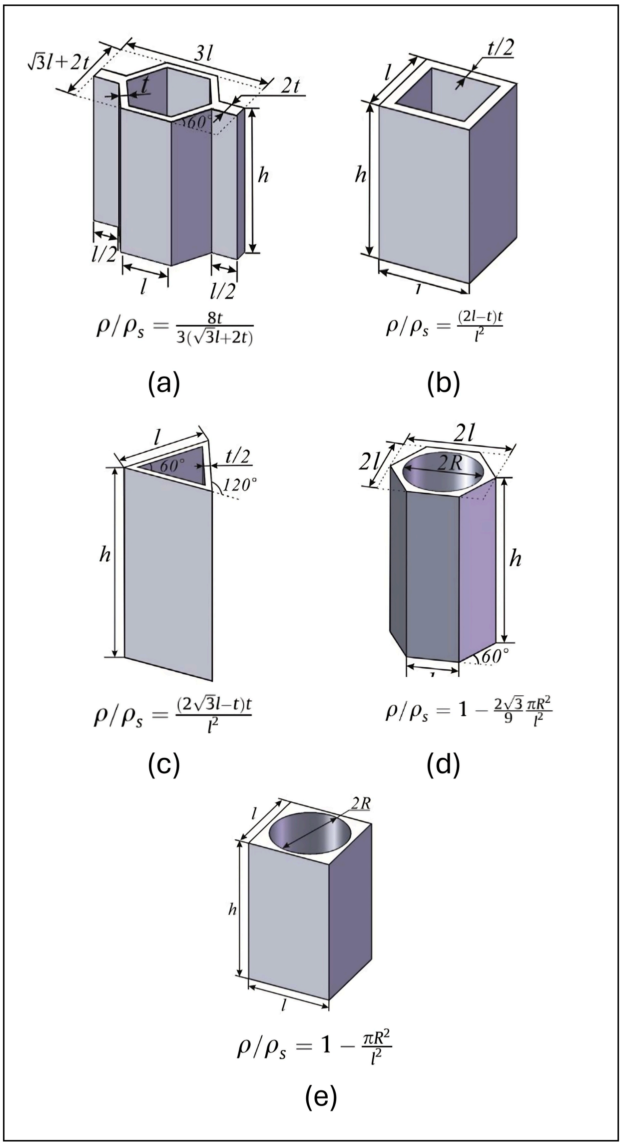


Fig. 2: Unit and relative densities of honeycomb of (a) Hexagonal, (b) Square, (c) Triangular, (d) Circular-cored hexagonal and (e) Circular-cored square (Shaik *et al.* 2015)

2.4 Bio-based Honeycomb Hexagonal cells

2.4.1 Hexagonal Building Concept

The hexagonal building concept comprised of a collection of drooping eyeballs that was connected similar to a honeycomb (as in those made by bees, wasps, and hornets). Most components may be connected using the smallest surfaces. Hexagonal building components are positioned adjacent to one another at their corners, allowing a row of polygons to be constructed along a longitudinal axis, according to the definition of hexagonal construction. Straight streets result from the uniform distribution of the longitudinal axis in a row parallel to the hexagon. It is still possible for the hexagonal building blocks to shape the borders of the equilateral triangles that are completed in a hexagonal star by those blocks because the parallel streets of the hexagon are alternately placed in the neighboring rows so that straight passing streets from three directions are cut at angles lower than 60°. These triangles were doubled in size to achieve the hexagon shape. A hexagonal structure (A B C D E F) was developed by connecting the center points of surrounding triangles with straight lines. The incorporation of a real building design's components into a honeycomb structure reveals the full potential of this natural concept. This innovative approach can be particularly beneficial in public gardens, where the triangular infill can provide additional functionality. A central building, such as a cafe, restaurant, or monument, serves as a focal point, while the surrounding triangle-shaped spaces can be utilized to create independent villas or interconnected structures, offering a unique and efficient use of space. (Rudolf, 1908). The hexagonal building concept is shown in Fig. 3(c).

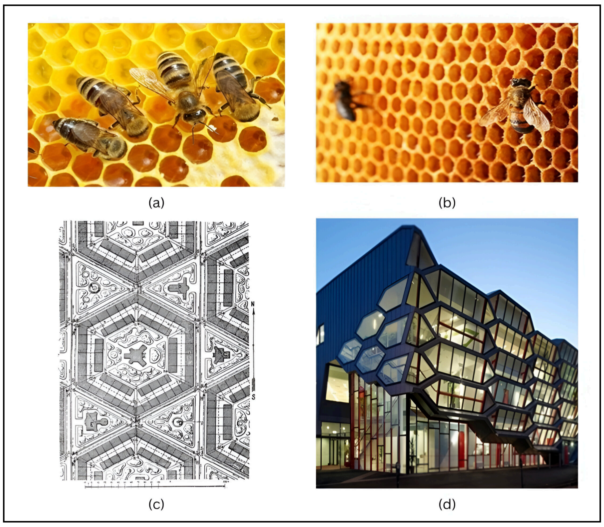


Fig. 3: (a) Beehives (b) Hexagonal honeycomb cells with bees, (c) Hexagonal building concept (Rudolf, 1908), and (d) Honeycomb architectural building

2.4.2 Hexagonal Architectural Concept

There are most fascinating scientific approaches existing in the world which are unimaginable to humans. Sustainable engineering supports the survival of the earth, disputing the harm caused by man-made engineering to the natural world. While our environment is shaped by human efforts, natural elements such as water, air, forests, plants, and animals represent remarkable examples of natural design. The inner structure of the beehive is a tightly packed collection of beeswax hexagonal prismatic cells known as a honeycomb. Honey and pollen are used by bees as nourishment to store cells and protect their young (eggs, larvae, and pupae). Engineers have recently learned that the structure of the beehive provide greater strength and protection. Consequently, constructions that require strength should be made in the form of a beehive. Fig. 3 showcase the inspiration and application of honeycomb structures in architecture, progressing from natural beehives.

2.5 Case Studies on Different Types of Honeycombs

A numerical and theoretical investigation was conducted by (Wang *et al*. 2020) on a composite cellular structure, known as honeycomb-filled circular tubes (HFCT), comprising round aluminum tubes packed within a honeycomb structure. The study aimed to analyze the mechanical performance of HFCT and compare it with traditional honeycomb and multi-tube structures. Using numerical modeling, the researchers validated the accuracy of their model by comparing computational data with actual data from a typical honeycomb structure. The validated model was then used to investigate the deformation behavior, minimum stress, and heat absorption properties of HFCT, traditional honeycomb, and multi-tubes. The study revealed that the interaction between the internal filler and the exterior container enhances the load bearing and energy absorption capabilities of HFCT. Simulation results showed that this interaction is primarily attributed to increased shear deformation of the cell and enhanced expansion and torsion of the foil. The findings demonstrated the advantages of HFCT, including its lower relative density compared to traditional honeycomb and multi-tube structures.

With reference to (Jeom *et al.* 1999), A lightweight structural design approach for transportation systems including airplanes, high-speed trains, and fast ships has been identified as aluminum sandwich construction. Both theoretical and practical research was conducted to examine the tensile properties of sandwich panels made from aluminum with an aluminum honeycomb core. On a sample of an aluminum sandwich panel, three kinds of tests were carried out such as three-point bending, bending stresses evaluation with (in-plane) compression loading, and crushing test with lateral forces. A stronger core can minimize the adverse effects of instabilities in the structure after the collapse, according to the findings of three-point bending tests on aluminum honeycomb sandwich beam specimens with varied honeycomb core cell thickness. The quality assurance and strength of the joints between the facing layers and the core would be critical to the collapse strength of sandwich panels, according to compressive collapse tests on aluminum honeycomb sandwich panel specimen. The core depth, core cell thickness, and panel equivalent diameter were among these parameters. According to the results of crushing tests performed on aluminum honeycomb sandwich panel specimens with different cell thicknesses and heights of the honeycomb core, facing skins significantly increased the crushing strength of the specimen when compared to tests using the bare honeycomb core. Certain straightforward crushing strength formulae allowed for reasonable estimates of crushing loads for bare honeycomb cores, but further research is required in this area to account for the impact of face layers on the behavior of crushing.

(Zongwen *et al.* 2020), fabricated reference to novel lightweight and environmentally friendly sandwich composite construction comprising sheets of basalt fibre resin and Nomex honeycomb with remarkable electromagnetic performance. It offers exciting alternatives in both developed and emerging sectors. The mechanical characteristics of flat-wise compression and bending tests using a sandwich composite construction was reinforced by Nomex honeycomb and basalt fibre. The height of the honeycomb has a significant impact on the compression strength of the specimen at a height of 10 mm, flat compression strength reaches its maximum value. The high honeycomb core will cause the honeycomb to lower the compression performance of the flat composite structure. The sheet thickness, honeycomb height, and honeycomb orientation are the three key variables that influence flexure qualities. The sheet thickness, out of all of them, has the biggest impact on the flexure properties. The flexure stiffness, shear strength, and flexure strength of the structure all increase with increasing thickness.

Xinyu *et al.* (2006) prepared a therm-hex using flat thermoplastic sheets. The interior sandwich panels for cars, where material designers are especially interested in the local compressive resilience and impact characteristics, are a possible application for this honeycomb. This study evaluated the compressive properties using FEA techniques. To commence, the linear buckling analysis (Eigen-value issue) of the honeycomb structures having various cell counts was used to ascertain the link between the single hexagonal unit cell and the infinite honeycomb. The unit cell model with or without flawed geometry was subjected to a nonlinear big deformation finite element analysis (FEA) to ascertain the compressive properties of the honeycomb. Thus, the honeycomb's modulus and strength are compared to those of the other analytical results and testing data. In addition, the compressive properties of honeycombs were investigated using both linear and nonlinear FEA. The results were compared to the FCTs and a few widely held theories. The nonlinear FEA on the improved unit cell model demonstrates a good forecast on the infinite thermoplastic honeycomb compressive modulus. The FCT-measured values were less than the infinite honeycomb quality predicted by the nonlinear analysis due to extra types of faults and the edge effect in the honeycomb samples. Due to convergence issues and the lengthy calculation time, nonlinear analysis of the honeycomb model was inappropriate with a significant number of cells.

YuanJing *et al.* (2008), prepared standard hexagonal honeycombs by brazing 0.49 mm thick Q215 plain carbon steel sheets in a vacuum furnace. The sheets were cut into rectangles with lengths between 80 and 210 mm and width between 15 and 25 mm, which match the height of honeycomb panels. Sandwich panels made of honeycomb-shaped plain carbon steel Q215 were brazed in a vacuum furnace. To identify their distinguishing characteristics, namely equivalent density, equivalent elastic modulus, and equivalent compressive strength along out-of-plane (z-direction) and in-plane directions (x and y-directions), studies were carried out utilizing an 810-material test system. The observed stress-strain curves show anticipated maximum compressive strains near solids up to 0.5–0.6 along out-of-plane and 0.6–0.7 along in-plane, which was in excellent agreement with the measured equivalent young's moduli and initial compressive strengths. The ratio of σ to π of these materials was comparable, even though 304 L stainless steel square honeycomb and Al alloy hexagonal honeycomb has higher compressive peak strengths than plain carbon steel regular hexagonal honeycomb.

Peilei *et al.* (2024) constructed 4D-printed cellular metamaterials using the shape memory polymer (SMP) such as polylactic acid as a primary material. This material has high stiffness, shape recovery properties, and energy absorption capabilities, since it can change its phase from glassy state and a rubbery state. The compression tests were performed using a SAAS electronic universal testing machine. The goal was to evaluate the mechanical properties, namely Negative Poisson's Ratio (NPR), Zero Poisson's Ratio (ZPR), and Positive Poisson's Ratio (PPR) of three types of cellular metamaterials structures. Four temperature conditions were applied such as 25 ℃, 40 ℃, 55 ℃, and 70 ℃ to observe how these structures responded under varying thermal conditions. The loading rate for the test was set at 8 mm/min, and the specimens were compressed until reaching the compacting stage. The tests revealed that all three types of cellular metamaterials exhibited predictable and stable mechanical properties at ambient temperatures. As the temperature increased, the mechanical strength and modulus of the materials decreased until reaching a glass transition point (around 63 ℃), beyond which the materials became more elastic. This behavior was well-known in the specimens made from Shape memory polymer (SMP)s, where the modulus and compressive strength curves evolved significantly with temperature.

PA 2200 powder, which is a nylon-based material of size 20 to 40 μm was utilized for selective laser sintering (SLS) to fabricate lattice structures with excellent mechanical performance. This material was employed for producing auxetic meta structures like 3D re-entrant honeycomb structures. A universal testing machine with a loading speed of 2 mm/min was used to apply compression on the Re-entrant-Arrow-Snake (RAS) structures. The test monitored the force and deformation behaviors of the structure using a sensor and digital camera. Tensile tests were conducted to measure the elastic properties of nylon specimens. Young's modulus and yield strength were derived from the stress-strain data. The RAS structure material has excellent stiffness, flexibility, and energy absorption, so it is utilized in fields requiring high energy dissipation and mechanical stability, such as medical stents or crash-resistant materials. The combination of physical tests and simulations provided a comprehensive understanding of its mechanical behavior.

2.6 Comparison Study on Various Properties

The physical properties and mechanical properties of various types of honeycombs (Dimitrios *et al.* 2020) are given in Table 1. The table presents a comprehensive comparison of the mechanical properties of five different materials, including Aluminum Alloy, Mild Steel, Nomex, Stainless Steel 304, and Thermoplastic. The results show that each material has its unique combination of properties, making them suitable for specific applications.

Table 1. Physical properties and mechanical properties of various types of Honeycombs

Material	Density (Kg/m³)	Poisson's Ratio	Yield Stress (MPa)	Young's Modulus (GPa)	Tensile Strength (MPa)
Aluminum Alloy	2660	0.3	125	70	90
Mild Steel	7850	0.3	250	207	440
Nomex	1380	0.389	233	3.13	816
Stainless steel 304	8000	0.265	205	193	515
Thermoplastic	80	0.42	31	1.3	27

2.7 Recent Innovations in Honeycomb Composites

2.7.1 Honeycomb-Filled Structures

In composite constructions, honeycomb-filled structures are preferred due to their advantages in the simplicity of production and up-front configuration. The concept of filling was initially presented in foam-filled constructions. Numerous fillers and containers were investigated to determine the ideal mix in (Zhong, 2019). Honeycomb cells filled with circular tubes (HFCT), the most recent filling pattern for composite structures, was a superb energy absorption structure. There are various similarities and differences between HFCT structures and other cellular-filled structures, such as metallic honeycomb structures and foam-filled structures. Other filling structures do exhibit the clear filling effect and matching effect, however, unlike honeycomb-filled structures, the honeycomb servers can no longer act as an exterior container for the HFCT structure. In this instance, the honeycomb cells inside the circular tubes offer the necessary imitations with respect to (Wang *et al.* 2018).

2.7.2 Embedded Honeycomb Structures

Honeycomb cells that were merged with foam, tubes, or polymer materials have substituted the honeycomb architecture. Unlike filled-type honeycomb designs, the embedded honeycomb was designed as a container rather than a filler (Zhong, 2019). To build a combined embedded improved honeycomb, that study integrated a single rib and rhombic grid combination into the hexagonal cell of the 2D re-entrant (CEEH). The new CEEH may depict effects with a negative Poisson ratio (NPR) and a zero Poisson ratio with the suitable geometric parameters in Young's module (ZPR). It was also discovered that by altering geometric parameters, CEEH may provide a wide range of Poisson ratio values (Chen *et al.* 2018).

2.7.3 Tandem Honeycombs

A tandem honeycomb was a design intended to extend the bounds of energy absorption for high-kinetic installations like steam engines and railroad wagons by combining several honeycomb blocks segments (Zhong, 2019). The tandem honeycomb structure attracted more attention as a freshly created hot composite structure and a specific form for the crash-worthy energy absorber design (Zhonggang *et al.* 2017).

2.7.4 Hierarchical Honeycombs

The structural hierarchy increased efficiency in several areas and make structural features more programmable (Zhong, 2019). Structures that linked to the addition of hierarchy improved elastic properties and damage tolerance. The honeycombs with hierarchical substructures were found to have excellent density, specific elastic, and energy-absorbing properties. Using simulation and finite elements, it was possible to examine the structural hierarchy and elastic properties of honeycombs. Several honeycombs with hexagonal, triangular, or square-shaped super and sub-structure cells were used to explore the consequences of introducing a hierarchy.

2.7.5 NPR Honeycombs

Negative Poisson's Ratio (NPR) honeycombs have excellent mechanical properties such as, shear modulus, notch resistance, fracture resistance, and durability toughness, and sandwich panels were made using such architectures (Zhong, 2019). The geometric characteristics of the honeycomb have a significant impact on its elastic modulus (Zhang *et al.* 2019).

2.7.6 Re-entrant Auxetic Honeycomb

A novel re-entrant auxetic honeycomb featuring similar inclusion was created to improve mechanical properties, including energy absorption and stiffness. As the redesigned honeycomb structure made self-contact during compression, its auxetic behavior significantly improved. Compared to the original structure, this resulted in a ten-fold increase in specific energy absorption. The study showed that self-similar inclusions improve the mechanical characteristics of honeycomb structures and improve their performance under compressive loads, which makes them perfect for applications in impact-resistant systems and protective gear (Xi *et al.* 2024).

2.7.7 Enhanced Re-entrant Honeycombs

The optimization of enhanced re-entrant honeycombs (ERH) aims to increase mechanical qualities including energy absorption and compressive strength. (Zeyao *et al.* 2024) used theoretical models and response surface (RS) methodologies to improve geometric characteristics for maximal performance. The theoretical model demonstrated great agreement with finite element analysis, confirming the accuracy of multi-objective optimization. The optimized ERH structure had an energy absorption capacity of 13.78 J/g and a Poisson's ratio of -1.06, indicating a balance between auxetic behavior and mechanical strength. The improved structure demonstrated enhanced deformation stability compared to traditional honeycombs, making it more appropriate for applications that require strong impact resistance.

2.7.8 Re-Entrant Combined-wall Honeycombs

Xiuhui *et al.* (2024) study investigated the in-plane quasi-static crushing behavior of reentrant combined-wall (RCW) honeycombs. The energy absorption improved by integrating hexagonal substructures within the walls of a typical reentrant honeycomb. The specific energy absorption (SEA) values of the RCW honeycombs were approximately doubled than the typical reentrant honeycombs, making it an excellent choice for impact resistance and energy absorption applications. Furthermore, the RCW honeycomb demonstrated exceptional design flexibility in terms of stress-strain response, enabling customized solutions in a variety of engineering applications. Experimental, computational, and analytical evaluations demonstrated that the RCW honeycomb retains a low Poisson's ratio and exhibits a transitional stress-enhancement stage during crushing.

2.7.9 Novel Auxetic Re-entrant Honeycomb Structure

The study on novel auxetic re-entrant honeycomb structure (NARH) focused on enhancing energy absorption during quasi-static and dynamic impacts by introducing V-shaped cell walls. The NARH structure developed more plastic hinges during deformation, resulting in larger plateau stresses and better energy absorption than traditional honeycomb designs. Numerical models revealed that the mechanical properties of the NARH were very sensitive to the incline angle of cell walls and impact velocity, making it highly adaptable to different impact situations (Yang *et al.* 2023).

3. RESULTS AND DISCUSSION

3.1 Various Studies on Honeycomb Columns

3.1.1 FEA of Aluminum Square Hollow Column

A computer analysis was conducted using a finite element model of a hollow structural aluminum column and an aluminum honeycomb, applying the Belytschko-Tsay uniform reduced shell integration rule, the hourglass stiffness prevention approach based on elastic modulus, and the Cowper-Symonds strain rate model. For columns made of aluminum, the typical finite element mesh size is 2.5 mm. The cell size, cell boundaries, and finite element mesh were all preserved at 1.5 mm x 1.5 mm to ensure a honeycomb connection. The Belytschko-Tsay uniform reduced shell integration technique was used to represent the carbon fibre tube finite element model in a manner that was comparable, and hourglass prevention was used as a plastic approach employing plastic modulus with an average mesh size of 0.5 × 0.7 mm. The force-displacement curve indicates that the performance and crashworthiness of a bare aluminum column can be enhanced by adding composite carbon fibre and aluminum honeycomb core as infill (Ji *et al.* 2018). Hollow aluminum columns and force-displacement curves are shown in Fig. 4(a) and 4(b) respectively.

3.1.2 FEA of Bitubal Columns

The mechanical properties of the columns made of aluminum alloy AA6060 T4, such as Young's modulus (E), initial yield stress (σ_y), ultimate stress (σ_u) Poisson's ratio (ν), and the power law exponent (n) were found to be 68.2 GPa, 80 MPa, 173 MPa, 0.3, and 0.23. The quadrilateral Belytschko-Tsay four-node shell element was used to simulate the entire sections, with five integration points employed through the thickness. A schematic illustration of bitubal columns and the finite-element model of Fig. 4(c) and 4(d) are given below. The results of the optimization technique demonstrated that the efficiency capacity of bitubal hexagonal columns with a fixed outer dimension can be improved by adjusting the thickness of the medial and lateral profiles while increasing the thickness of the core walls. An acceptable side length for the innermost profile must also be selected in order to get the optimal design with the most energy absorption. The column with the highest average force and energy dissipation also has the highest different energy absorption (SEA) since all columns have the same mass (Zhang *et al.* 2008).

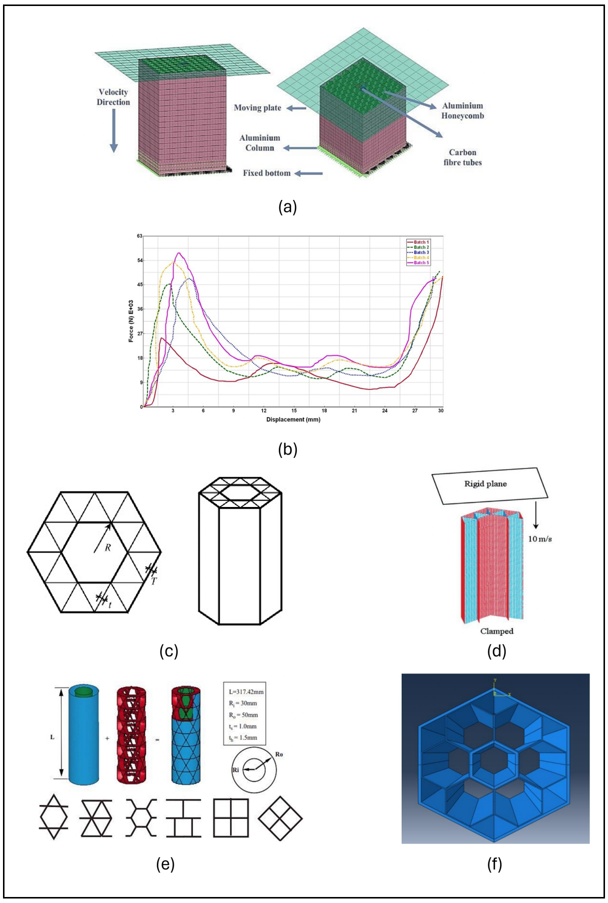


Fig. 4: (a) Hollow aluminum column with three carbon fibre tubes in a honeycomb-filled (Ji *et al.* 2018), (b) Axially compressed hollow columns (Batch 1), hollow columns filled with honeycomb (Batch 2), hollow columns with one carbon fibre tube and one filled with honeycomb (Batch 3), hollow columns with two filled with honeycomb (Batch 4), and hollow columns with three filled with honeycomb (Batch 5) are examples of common force-displacement curves from numerical simulations (Ji *et al.* 2018), (c) Schematic illustration of bitubal columns (Zhang *et al.* 2008) (d) FEA model (Zhang *et al.* 2008, (e) Honeycomb sandwich column geometrical configurations (Zonghua *et al.* 2011) and (f) Honeycomb column

3.1.3 Cylindrical Columns with Sandwich and Foam Infill

The hemispheric thin-walled tubes with outer (R_o) and inner (R_i) radii of 50 mm and 30, respectively, have walls that were 1 mm thick. Sandwich columns constructed using kagome, triangular, and hexagonal patterns have a total length of 317.42 mm, while those made with square-3, square-4, and diamond patterns measure 314.16 mm. The interleaved core consists of a tubular large-cell honeycomb lattice resembling the interlocking topology of a planar honeycomb plate. Each honeycomb cell measures 1.5 mm, and six cells define the boundaries of each honeycomb core. A finite element model was created in ANSYS/Preprocessor using Belytschko-Tsay four-node shell elements to connect the thin-walled tubes and the honeycomb core. Honeycomb sandwich column configuration is shown in Fig. 4(e). The honeycomb sandwich contrasted with the columns loaded with foam. The two varieties of sandwich columns placed greater emphasis on collision forces and energy dissipation compared to empty, thin-walled tubes. Additionally, the honeycomb sandwich columns, particularly the Kagome sandwich column, demonstrated superior thermodynamic performance compared to foam-filled columns, except when tightly bound fillers were used (Zonghua *et al.* 2011).

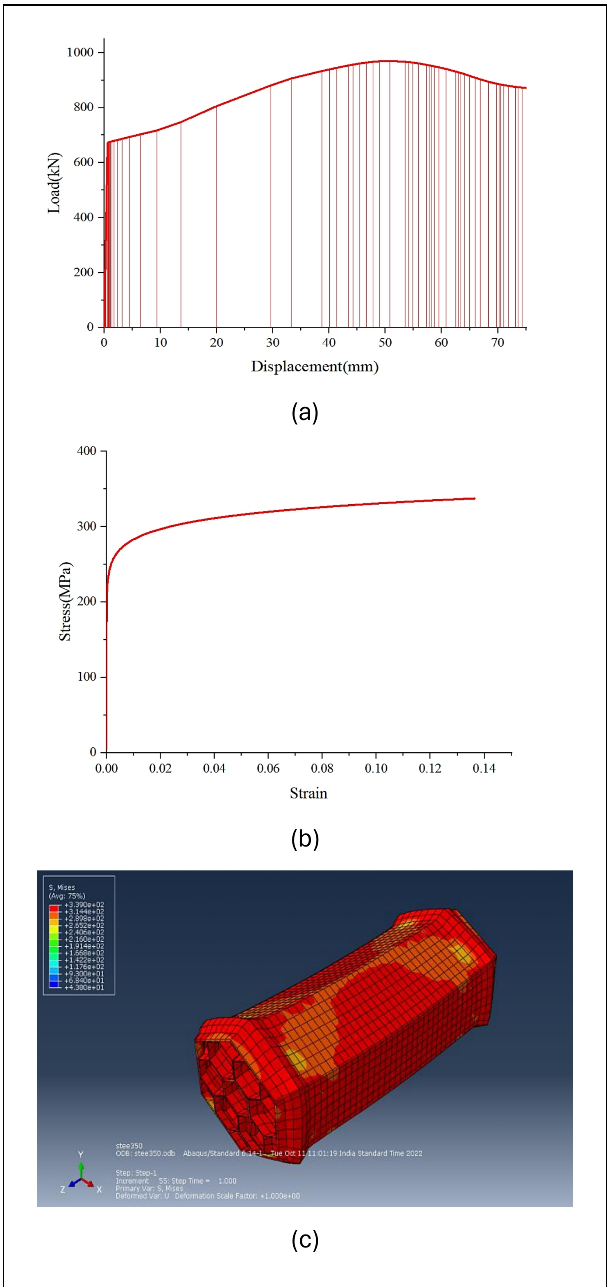


Fig. 5: (a) Load versus Displacement, (b) Stress versus Strain and (c) Failure of mild steel column

3.2 Numerical Modelling of Honeycomb Columns

The modelling of Honeycomb columns had been analyzed by using Abaqus 6.14 software tool. The analysis was done for the entire column to find out stress, strain, load, and displacement. A model of the Honeycomb column is shown in Fig. 4(f).

3.2.1 Mild Steel Honeycomb Columns

Steel St.37 is an abundant element in the industry. It is lightweight, corrosion-resistant, similar to AISI 1045, and had excellent heat conductor with chemical components of 0.5% carbon, 0.8% manganese, 0.3% silicon, and other components. It has a hardness of 170 HB and a tensile strength of 650–800 N/mm^2 (Junaidi *et al.* 2018). Table 2 lists the plastic characteristics of mild steel, and specifics of the specimen St.37 used for the numerical research and the experimental results obtained from our investigation. The load versus displacement curves, stress versus strain curves, and the failure of the specimen are shown in Fig. 5. Mild Steel exhibited a relatively moderate numerical load of 970.1 kN with a high displacement of 50.82 mm. The mild steel column deformed plastically at a yield stress of 251 MPa, progressing to 339 MPa at a strain of 0.174. The load-displacement and stress-strain relationships showed that the material underwent significant deformation before failure.

Table 2. Plastic properties of mild steel St. 37, Specimen details and numerical results

Yield stress (MPa)	Plastic strain
251	0
264	0.024
295	0.049
316	0.074
326	0.099
334	0.124
336	0.149
339	0.174

Sp. No.	Outer tube Thickness (mm)	Inner tube thickness (mm)	Core Thickness (mm)	Height (mm)
S1	3	3	1	500

Sp. No.	Numerical Load (kN)	Displacement (mm)	Stress (MPa)	Strain
S1	970.15	50.82	339	0.136

3.2.2 Aluminum Honeycomb Columns

Utilizing technologies identical to that for steel sheet metal, aluminum sheets can be folded and welded into straightforward forms. Although softer and less rigid than stainless steel, aluminum has great heat conductivity.

Therefore, compared to carbon or stainless-steel moulds, aluminum moulds often have larger walls. Grit blasting and chemical etching were very simple ways to texture aluminum, which was also easily machined (Roy and Throne, 2002). Table 3 following lists the plastic characteristics of aluminum, specifics of the aluminum specimen used for numerical research and the experimental results obtained from our investigation. The load versus displacement curves, stress versus strain curves, and the failure of the specimen are shown in Fig. 6. Aluminum shows the highest stress at 563.4 MPa with a higher load of 1051.66 kN, but the displacement was lower at 27.59 mm, indicating a stiffer response compared to mild steel. The aluminum column exhibited a wide range of plasticity, reaching a plastic strain of 2.1. This indicates that aluminum had a higher energy absorption capacity before failure, which may make it suitable for applications where lightweight materials with significant deformation were preferred.

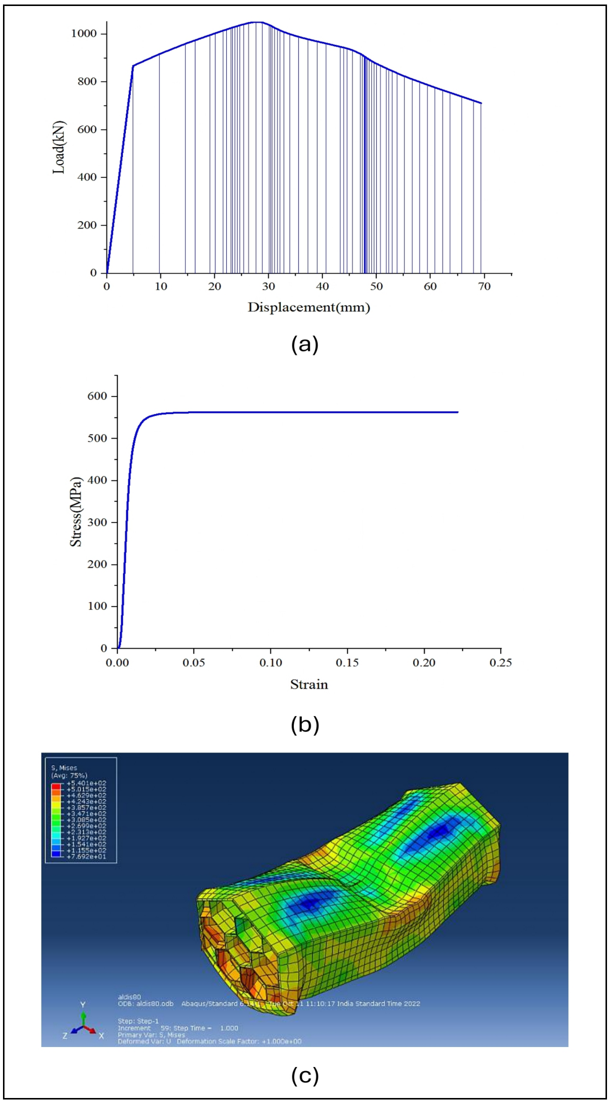


Fig. 6: (a) Load versus Displacement, (b) Stress versus Strain and (c) Failure of Aluminum Column

Table 3. Plastic properties of Aluminum, Specimen details and Numerical results

Yield stress (MPa)	Plastic strain
311	0
316.64	0.0034373
324.52	0.0085932
365.52	0.045329
383.7	0.071431
401.65	0.11058
434.74	0.25741
455.35	0.38955
485.16	0.58775
529.75	0.88507
596.64	1.331
696.98	2
696.98	2.1

Sp. No.	Outer tube Thickness (mm)	Inner tube thickness (mm)	Core Thickness (mm)	Height (mm)
S1	3	3	1	500

Sp. No.	Numerical Load (kN)	Displacement (mm)	Stress (MPa)	Strain
S1	1051.66	27.59	563.4	0.22

Table 4. Plastic properties of high-strength steel, Specimen details and Numerical results

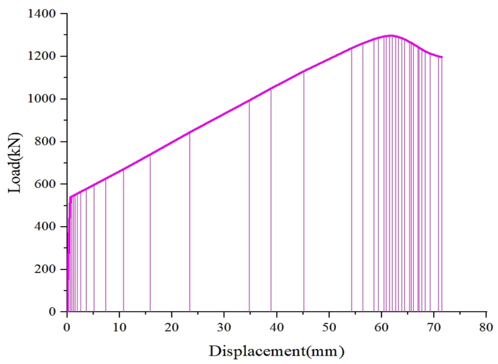
Yield stress (MPa)	Plastic strain
200	0
246	0.0235
294	0.0474
374	0.0935
437	0.1377
480	0.18

Sp. No.	Outer tube Thickness (mm)	Inner tube thickness (mm)	Core Thickness (mm)	Height (mm)
S1	3	3	1	500

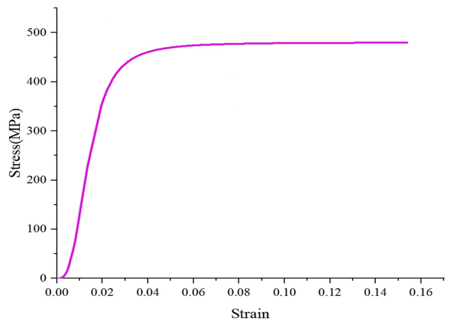
Sp. No.	Numerical Load (kN)	Displacement (mm)	Stress (MPa)	Strain
S1	1297.02	61.49	480	0.153

3.2.3 High-strength steel Honeycomb Columns

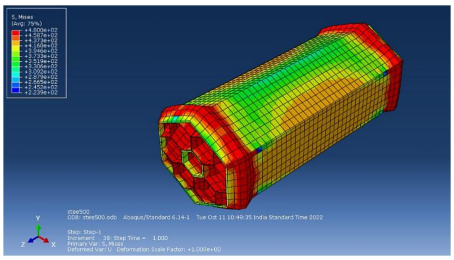
High-strength steels are sometimes known as structural steels since they were typically employed in structural applications. It was possible to add or remove a small number of micro alloying components during production. High-strength low-alloy steels, sometimes referred to as HSLA steels, were produced by micro alloying elements such as Cb, Ti, Mo, and V. Due to their low carbon and alloy content, these grades offered adequate processability, along with strength and ductility, and exhibit outstanding weldability. Complex forms can be more challenging to form than mild steels, but effective components can be produced with appropriate die design and analysis. Table 4 following lists the plastic characteristics of High-strength steel, specifics of the high-strength steel specimen used for numerical research and the experimental results obtained from our investigation. The load versus displacement curves, stress versus strain curves, and the failure of the specimen were shown in Fig. 7. High-Strength Steel shows the highest numerical load capacity at 1297.02 kN and substantial displacement of 61.49 mm. High-strength steel had a plastic strain range similar to mild steel but reached much higher yield stresses, reflecting its increased load-bearing capacity. The load-displacement curve of the material showed both strength and ductility, indicating its potential use in high-performance structural applications where both these properties were critical.



(a)



(b)



(c)

Fig. 7: (a) Load versus Displacement, (b) Stress versus Strain and (c) Failure of High-Strength steel column

4. CONCLUSION

Steel is regarded as the most notable and powerful material when compared to all other material components, according to research on honeycomb composites. Even though the honeycomb pattern has the best form among all other patterns, the strength and features vary depending on the type of composite used. Most structural components in modern studies are planned and studied utilising a variety of digital tools before implementing on-site activities. Using Abaqus 6.14, the mechanical properties of the honeycomb columns formed from a variety of materials, which include mild steel, aluminum and high-strength steel, were analyzed. The findings showed that the high-strength steel honeycomb columns could indeed withstand higher loading during axial compressive strength tests with a maximum displacement of 61.49 mm. The findings indicate that the maximum stress for mild steel was 339 MPa, and the maximum strain was 0.136. High-strength steel had maximum stress of 480 MPa with a strain of 0.153, while aluminum had maximum stress of 563.4 MPa with a strain of 0.22. On comparing the results, it was clear the more stress results in greater strain. Comparatively, the aluminum honeycomb columns achieved the most stress and strain, however, as per the strength tests, aluminum obtained a reduced displacement of 27.59 mm, resulting in 1051.66 kN. Additionally, at the lower displacement, the top of the aluminum columns was slightly compressed, the central section was bent. However, the mild steel and high-strength steel columns failed at a later stage due to compression at the top and bottom of the section as well as the departure of honeycomb cores at the middle area, with the maximum displacement being 50.82 mm and 61.49 mm, respectively. It demonstrated that breakdown of the component-based material will eventually be delayed when displacement increases. The numerical results showed that the choice of material depends on the specific requirements of the application. Mild steel is suited for applications based on large deformations and ductility. Aluminum is ideal for lightweight structures with high strength, and high-strength steel excels in applications requiring both high load-bearing capacity and significant deformation. Thus, the selection between these materials should consider factors like weight, strength, deformation, and failure mode to meet the performance criteria in engineering design. The best material for the honeycomb structural component, according to the component research, was steel because of its durability and strength. Axial compression stress offers aluminum a higher strength, but the material is more prone to failure due to bending.

In future, many innovative approaches are needed for solving complicated problems in structural and non-structural activities.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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