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Comparative Finite Element Analysis of Hybrid Polymer Composite for Design in Marine Bulkhead and Ship Hull

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Abstract: The paper revolutionises the engineering field since material plays a major role in engineering applications. Several applications require the best material. Researchers are compelled to use a Reinforced Synthetic Hybrid Composite material comprising Kevlar, eggshell, human hair, and banana spathe in bulkheads and hulls. The mechanical and thermal properties are compared to identify the enhanced material in a Finite Element Analysis using ANSYS software. This hybrid synthetic composite material can enhance mechanical properties (tensile strength, impact, and maintain strength) as well as resilience down to cryogenic temperatures. It can be used in applications such as bulkheads and hulls. Researchers have performed thermal conductivity testing in accordance with ASTM standards to determine each sample's thermal conductivity. Then, researchers will examine the material's mechanical and thermal behaviour through finite element analysis and compare each sample to identify the appropriate material. From our observations, a Kevlar + eggshell composite has higher tensile strength. The thermal properties of the Kevlar + banana spathe sample are good. This hybrid composite material performs well under racking, hogging, and sagging loads, as well as under corrosive conditions, making it suitable for ship bulkheads in marine construction.

Keywords: Mechanical Properties; Hybrid Composite; Thermal Behaviour; Marine Construction; Engineering Applications; Banana Spathe; Ship Bulkhead; Tensile Strength; Human Hair.

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1. Introduction

A new class of engineered materials, composite materials, is made by combining two or more different substances and exhibits properties that are not individually demonstrated by the components themselves. This unique combination will improve composite performance, such as strength, weight, durability, or physical or chemical properties, beyond what can be achieved

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with a material used alone. Due to these, sources vary to achieve tremendous versatility and efficiency in constituent materials and processes that cater especially to specific design and function requirements. Whether in aerospace, automotive construction, or marine applications, by providing innovative solutions to the most complex challenges, composites, especially composite laminates, are an absolute must in modern engineering [1]. Amongst many factors that make composites so ubiquitous across the world, perhaps one factor stands above the rest: an impressively excellent strength-to-weight ratio. That strength-to-weight ratio provides fine structural strength without weighing considerably more than equivalent conventional materials, which are inherently metallic. For instance, carbon fibre-reinforced composites are a clear example of an advantage. They are five times stronger than 1020-grade steel but weigh only one-fifth as much, making them ideal for weight-sensitive applications such as aircraft components, racing cars, and high-performance sporting goods [2]. This blend of better strength and lighter weight means high efficiency in all those industries. Using aerospace-grade materials would reduce fuel consumption and increase payload capacity. And in the automotive industry, they help achieve greater fuel economy and better vehicle performance. Even though aluminium is considered lightweight, it cannot match the impressive properties of carbon-fibre composites. Aluminium is well known for its favourable weight-to-strength ratio, but it cannot compete with the exceptional modulus and strength of carbon-fibre composites. These composites have been reported to be 7 times more potent than aluminium in some applications.

They are therefore more revolutionary in demanding applications [3]. In advanced manufacturing, carbon fibre composites are used to produce components that are stiffer and more resistant to deformation. Thus, they become critical in precision-driven industries like robotics and medical devices. The versatility of composites extends beyond their mechanical performance; they can be engineered to include features such as corrosion resistance, thermal stability, and electrical conductivity. Thus, they can be made to fit almost any environment, from the deep sea to space, and even extreme temperatures. Hybrid composites, using recycled and virgin fibres to further sustainability, will not pose a threat to the environment, especially given the mounting environmental problems. Because composite materials are highly attractive, with excellent properties, and continue to improve through innovations in materials science and processing, composites remain ahead of their counterparts in engineering solutions for current problems and those expected in the near future. Whether it is about replacing traditional materials or enabling new technologies, the field of composites is advancing in materials science. From all aspects, the sector remains dynamic, with ongoing and unprecedented developments across the materials, process, and application fronts. Hybrid combinations, from virgin to recycled fibres, to even automated, faster manufacturing systems, are changing the marketplace [4]. That reflects into composites growth: this global composites market has approximately a 5% year-over-year growth rate, while individual growth in carbon fibre is said to be around 12% annualised. Composites showcase such fabulous advantages, although in many ways, only special ones have unique strong/weak points that they do not fail to identify unless during the design/specified stages [6]. That is to say, composites are not typically versatile for all applications, but their versatility can make them suitable for specific properties, such as a fire-retardant matrix to resist fire or superior fatigue resistance to prolong product lifetimes [7].

Multi-domain advantages of composites involve higher specific strength and stiffness. This leads to reductions in fuel consumption, improvements in acceleration, and extended range in transport systems [8]. Lightweight structures are easy to install and thus do not load the supporting systems, such as robotic arms or offshore platforms [9]. Composites are very helpful in marine and chemical environments because they do not corrode, so no coatings are needed that would otherwise require high maintenance [10]. Composite bearings in marine engines and bridges are examples of applications that benefit from self-lubricating and corrosion-resistant properties [11]. The composites are highly efficient at providing thermal insulation and have good applications in fireproofing, blast resistance, and cryogenic applications [12]. In the shipbuilding sector, components such as bulkheads and hulls require a high strength-to-weight ratio. Bulkheads provide critical partitions in ships that prevent cargo from lurching, and the watertight integrity is provided by the hulls [13]. Composite materials have increasingly been adopted through the layered lamination approach to achieve the target strength and stiffness in these applications [14]. Advanced computational techniques, such as Finite Element Analysis, are used to analyse and optimise these materials [15]. FEA uses a mesh of small elements to solve complex structures; it has no equal for accuracy in stress, displacement, and support reaction analysis [16]. It optimises the mesh size to improve accuracy and enable the analysis of complex shapes, thereby supporting product development in material design [17]. The basis for developing, optimising, and applying composite materials is the application of specialised software in engineering design and analysis. It enables engineers to conceptualise, model, simulate, and analyse complex structures with unprecedented accuracy. Advanced software such as AutoCAD, CATIA, Pro/E/Creo, SolidWorks, and ANSYS can be used with great sophistication to design and test composites; in doing so, the full range of structural integrity, performance, and failure modes can be analysed in detail. It supports all engineering processes, from conceptual design to final verification, ensuring that the selected materials meet specific needs and perform well under many conditions [18].

These software tools help provide better insight into such complex composites and how they behave under external forces, environmental conditions, and long-term applications. During our current work, studies have been conducted on Kevlar hybrid composites as potential replacements for traditional steel bulkheads used by marines. Of all the materials known thus far, Kevlar offers unmatched strength, is lightweight, and is corrosion-resistant, making it ideal for highly stressed applications such as marine engineering. Researchers tried to improve its mechanical properties while reducing production costs by adding Kevlar and hybridising it with other materials, such as eggshell powders, banana spathe, and human hair. This hybridising design leverages the strength of another component material. Such a process, on the other hand, supports sustainable engineering by utilising natural and recycled materials for reinforcement [19].

Research studies show that Kevlar-based composites exhibit excellent bending and tensile strength properties relevant to structural applications; in this context, they can support bulkheads, withstand heavy loads without distortion, and withstand significant deformation in marine fluid environments. Other reinforcements, such as eggshell powder, enhance mechanical properties through increased compressive strength, while banana spathe fibres and human hair enhance flexibility and resilience. Thus, hybrid composites possess the above properties with fewer self-maintenance periods and increased service life. Another added advantage of using a corrosion-resistant material is Kevlar, which performs significantly better in marine conditions. Severe conditions, coupled with seawater, accelerate the degradation of traditional materials [20]. The use of simulation tools, as provided by ANSYS software, in this kind of study models performance evaluation at the laminate layer level. Such a simulation at a higher level of advancement can predict the behaviour of a composite under various stress conditions and optimise layer orientation, which is then verified through structural integrity testing. Hence, such a hybrid material is added to these simulations, ensuring that the product is not only useful but also cost-effective and environmentally friendly. This leads to accurate 3D models in SolidWorks, and visual inspection enables iterative design improvements. In short, advanced design software and the innovative application of Kevlar hybrid composites open a new frontier in material engineering for marine environments. They enable lighter, stronger, and more sustainable alternatives, opening the door to cost-efficient, high-performance solutions in conditions where traditional steel construction faces challenges. This will underpin the change potential at the interface between modern engineering tools and innovative materials science.

2. Literature Review

These topics of thermal conductivity and resistance are vast and crucial to research to date, due to ever-growing demands for sustainable efficiency and materials. Analytical tests have been carried out; some experiments include banana composites and even pineapple and jute combinations, to precisely determine whether its capacity would allow it to provide perfect thermal insulation. In these experiments, the insulation thickness is evaluated using copper tubes that emit heat, and the resulting thermal conductivity and resistivity values are determined as analysed in studies by Yogita and Medhane [3]. It shows the maximum and minimum values of thermal conductivity and resistance for any composite composition, in relation to other composites, making the material applicable in appropriate areas. Such results have significant applications, especially in industries that require proper thermal insulation [4]. Other similar studies also included the design and stress analysis of steam turbine blades, which are fundamental components in wind plants, ships, and large power plants. Engineers have used finite element analysis to assess the dynamic behaviour of these blades; they have ensured that, even as they impose pressure and centrifugal loading on the blades, the stresses developed remain within allowable limits and that, once built, the blades will also be structurally strong [5]. The work on composite materials has remained relevant due to the need to reduce weight and enhance strength in modern engineering applications [6]. For instance, vibration analysis of E-glass epoxy fibre-reinforced plastic (FRP) has shown that it has higher free vibration frequencies than steel, as reported in Songra [7]. This improvement results in better performance in applications involving weight and vibration control. It even establishes, through various analytical methods, that theoretical analysis aligns with experimental results, indicating that composite materials are highly reliable when designed per engineering principles [8].

Besides this, the thermal characterisation of composites compared and evaluated several different material systems to assess the heat-flux characteristics of materials, as reviewed in detail by Dinesh et al. [9]. The experimental setup, using tools such as thermocouples and voltmeters, shows that materials with lower heat flux exhibit better thermal resistance [10]. This capacity for fine-tuning thermal properties makes composites ideal candidates for insulation and energy-efficiency designs [11]. Subsequent studies on heat transfer through composite walls have employed analytical and finite-element methods to provide more detailed information on temperature distributions, heat fluxes, and heat transfer rates [12]. It has been shown that, for the same material combination, such as MS-hylum-wood and MS-concrete-fibre, lower heat flux values yield better insulation [13]. This is useful information in applications requiring good thermal barriers [14]. In parallel, delamination buckling analysis of composite plates has provided insight into structural stability characteristics of delamination patterns, as discussed by Ewins [15]. Researchers have shown that imposing boundary conditions and compressive loads significantly reduce the buckling load capacity, underscoring the importance of proper material selection and design strategies in structural applications [16]. Composite rail ties are analysed and compared to steel using finite element analysis [17].

From these analyses, composites are projected to be superior in tensile strength at much lower weight. FEA simulations match the results of experiments. Consequently, composites were observed to be effective for deformation and durability, as reported in Caramatescu and Mocanu [18]. The mechanical performance of epoxy composites reinforced with banana fibres at different percentages has been studied. Additionally, it has been well proven that the higher the fibre length, the greater the resistance to deformation and the lower the stress forces [19]. These results reveal that natural fibres can enable the production of high-performance composite materials [20]. Delamination modelling of composite beams has enhanced knowledge of their use in demanding structural applications, such as aeroplane wings. Their findings reveal that composites with glass fibres have better lifetimes and safer margins than their carbon counterparts, especially under static, modal, or fatigue forces [3]. Such discoveries were crucial for dependability and durability in certain cases. Exploratory research at the laboratory scale on natural and synthetic hybrid composites for marine use has evaluated tensile strength, impact resistance, and moisture absorption [4]. For instance, the tensile properties of Kevlar hybrid composites prepared with eggshell and coir fibres have been improved due to optimised fibre lengths and reduced fibre content, making them ideal for the construction of marine structures [5]. The summation of all these works demonstrates a wide potential of composite materials for different applications. Highly sophisticated experimental techniques and very powerful tools, such as finite element analysis, were used to validate and optimise composite materials in terms of strength, thermal resistance, and structural stability [6]. Such development is required in industries such as marine engineering, aerospace, and renewable energy, as that material is essential. The ability to govern the properties of composites on demand will ensure the continued validity of composites as they expand into ever-wider applications in modern engineering [7].

2.1. Problem Identification

- The design of the composite material is not given, which makes it clear that the testing by analysis is wrong.
- Often, the structural strength of all composites is highly required; only thermal properties and their identification are concluded.
- Most concluded that the composite is non-biodegradable, which is very difficult given the current trend toward more by-products (waste).
- Every composite has a specific orientation and layup plies, which are not described and are unavailable.
- Certain analyses need tests to be done, and based on that data, results are concluded and compared with the design analysis.

2.2. Research Gap

In the engineering field, a lot of research and new inventions are taking place in materials. The analysis also makes the biggest revolution in the engineering field. So, researchers will analyse the material in a research paper. Many composite and hybrid composite materials are used in various engineering applications and are analysed using various methods. Recently, Kevlar Hybrid composite materials made from eggshell, Banana spathe, and hair were discovered and experimentally tested [10]. But no one has analysed the material using the finite element method. Researchers studied the material in detail and are now analysing it to determine its mechanical and thermal behaviour using the finite element method.

3. Methodology of Study

To add to this, this paper applies a comparative FEA to assess the mechanical and structural performance of a hybrid polymer composite in different marine applications, such as bulkhead and hull ship design. This work focuses on a selection of materials, using a hybrid polymer composite for fabrication within a polymer resin that incorporates fibres of carbon, glass, and aramid. Therefore, these materials are selected based on their mechanical performance, durability, and other properties suitable for marine environments. Input parameters include standard material testing data, such as tensile, compressive, and flexural strengths, as well as environmental resistance. With software such as ANSYS or Abaqus, detailed models of a bulkhead and a ship hull section are developed. Models are developed to effectively represent realistic geometries, along with appropriate loads and restraints, in their marine applications. Hybrid composites are then compared with conventional materials such as steel and aluminium under static and dynamic loading conditions, including hydrostatic pressure, impact loading, and wave-action-induced fatigue cycles. Thermal and environmental degradation simulations are also considered for an extended period for the performance evaluation. Based on the above simulations, key performance metrics will be evaluated through stress distribution, deformation weight reduction, and modes of failure.

Studies on parameter variations focus on parametric variations in fibre orientation and stacking type, with resin properties influencing overall performance. Wherever possible, comparisons with the experimental results and other available literature have been used to cross-check the work. Based on these observations, optimal hybrid composite configurations for marine bulkhead and ship hull designs are proposed, with a focus on weight efficiency, corrosion resistance, and long-term durability. Consider: In the engineering field, much research and new inventions are underway in materials. The analysis also makes the biggest revolution in the engineering field. So, researchers will analyse the material in a research paper. Many composite and hybrid composite materials are used in various engineering applications and are analysed using various methods. Recently, Kevlar Hybrid composite materials made from eggshell, Banana spathe, and hair were discovered and experimentally tested [10]. But no one has analysed the material using the finite element method. Researchers studied the material in detail and are now analysing it to determine its mechanical and thermal behaviour using the finite element method. Composites are selected based on requirements in marine applications such as hulls and bulkheads. Our assumption in choosing composite lamina such as Kevlar, eggshell powder, banana spathe, and hair is that each offers better performance because it has a higher strength-to-weight ratio, greater impact energy absorption, higher flexural strength, greater thermal resistance, and is primarily biodegradable. They are mainly fabricated by hand layup.

First, the samples are purchased and obtained naturally. The correct amount of epoxy resin LY556 is premixed and homogenised with hardener HY 952 at a 10:1 ratio, and the composite mixing ratio is 40:60 by volume. The different samples were collected and prepared separately: eggshell with 5% NaOH and banana spathe, and the hair was finally dried for 24 hours. Epoxy is coated over the base material, i.e., Kevlar (bottom layer), and the lamina, such as eggshell powder, hair, and banana spathe, is applied over the coated epoxy, then coated again with Kevlar (top layer). The three samples of Kevlar+hair, Kevlar+eggshell, and Kevlar+banana spathe are designated as samples 1, 2, and 3, respectively. Samples 1 and 2 were made into five layers, and sample 3 into three layers. Once the coating is applied layer by layer, the wax is placed on the material over the tile, and a constant load is applied per the hand-layup technique. Each of the three samples is given 24 hours to dry. The hybrid composite material consists of three samples, and each sample has a different Thickness of ply layers. Sample 1 has a thickness of 6.3mm, sample 2 has a thickness of 4.4mm, and sample 3 has a thickness of 6.1mm. Each sample has five plies bound by resin. The thermal conductivity in Table 1 below is from testing a sample specimen. By heat analysis, the thermal conductivities of three samples are obtained. All material thicknesses are taken in accordance with the testing standards ASTM E1530 and ASTM D790.

Table 1: Material dimension

No.	Sample Name	Material Name	Length(mm)	Breadth (mm)	Total Thickness (mm)
1	Sample 1	Kevlar + hair	50	50	6.3
2	Sample 2	Kevlar + eggshell	50	50	4.4
3	Sample 3	Kevlar + banana spathe	50	50	6.1

Table 1 provides the dimensions and total thicknesses of three hybrid composite samples, in which Kevlar was the primary reinforcement and various natural fillers were used. All samples are of equal length and breadth (50 mm by 50 mm) but vary in total thickness, depending on the natural filler and the thickness of the Kevlar layer. Sample 1 with human hair and Kevlar has a maximum thickness of 6.3 mm; it therefore enhances cushioning and shock-absorbing ability due to the added hair layer. Sample 2, containing eggshell, shows a minimum thickness of 4.4 mm. It also possesses a more solid structure. This may even be an advantage for some applications, such as a low-profile design that requires light but rigid parts. Sample 3 with banana spathe as a filler has a total thickness of 6.1 mm, very close to Sample 1 but slightly thinner, indicating that rigidity and flexibility have been balanced. The variation in thickness across the samples indicates how the filler material will affect the composite's structural profile, which, in turn, will determine its applicability. Although human hair and banana spathe provide slightly thicker configurations, therefore more rigid, the hardness of an eggshell suits applications where streamlined and compact designs are in demand. This would imply consequences in tailoring composite structures to meet especially specific demands in marine engineering: balancing a heavy body with flexibility and durability.

Table 2: Material data

No.	Sample Name w/ layer		Young's Modulus (GPA)	Poisson's Ratio	Thermal conductivity (W/mk)
1	Sample 1	Kevlar-29	70.5	0.35	0.174
		Epoxy resin	3.4	0.3	
		Human Hair	1	0.391	
2	Sample 2	Kevlar-29	70.5	0.35	0.227
		Epoxy resin	3.4	0.3	
		Eggshell	10	0.3	
3	Sample 3	Kevlar-29	70.5	0.35	0.164
		Epoxy resin	3.4	0.3	
		Banana spathe	3.48	0.28	

The comparative analysis in Table 2 will consist of three composite samples: all of these samples have comprised Kevlar-29 and epoxy resin, but with different natural filler materials. Sample 1, on human hair fillers, has a moderate thermal conductivity of 0.174 W/m·K and flexibility, anlong with taisson ratio of 391, so it has lowhelowerонductivity than the sthan Sample 2 consisted of eggshell as the filler, and the highest thermal conductivity was obtained by that sample, which is 0.227 W/mK because of the higher stiffness properties and Young's modulus of eggshells were around 10 GPa; this will promise a good application, which requires efficient transfer of heat. Sample 3, using banana spathe as filler, had the lowest thermal conductivity of 0.164 W/m·K, and Poisson's ratio decreased slightly to 0.28. This, therefore, implies a balance between flexibility and insulation in heat transfer. All the samples showed a Young's modulus of 70.5 GPa. Still, the Poisson's ratio was measured in the Kevlar-29 layer at 0.35, and the epoxy resin layer provided uniform bonding and average mechanical support, with an average Young's modulus of 3.4 GPa. The results show how natural fillers modify composite properties. Thermal properties are enhanced with the inclusion of eggshell. Human hair added flexural strength to the banana spathe, further optimising insulation for engineered applications to various marine requirements. Figure 1 shows the layer formation in our hybrid composite material. There are four types of lamina: woven, bi-directional, dis-oriented, and uni-directional. The Kevlar has a woven fibre structure, whereas the eggshell has a disoriented fibre structure, and both the banana spathe and hair have bidirectional fibre structures. These fibres are arranged as shown above, then made into plies. Finally, these pieces are manually pressed after being covered with a resin bond, and the resulting composite samples are separated into 3 (1, 2, 3).

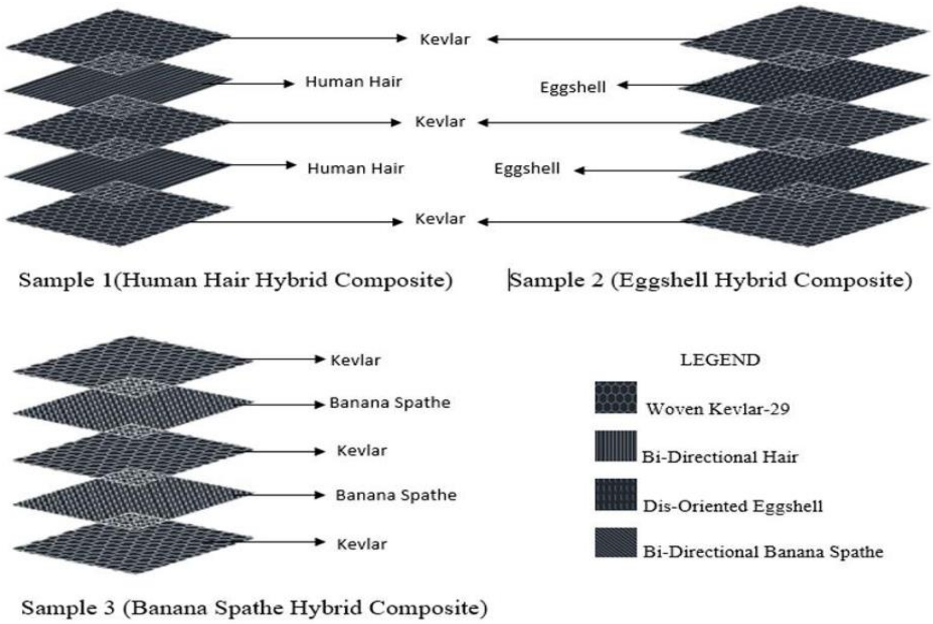


Figure 1: Layer foundation

Epoxy resin is the major structural adhesive and engineering adhesive used in human life applications. It has high-performance bonding strength. In addition, epoxy resins have been developed for a wide range of applications. It can be used for metal, glass, and plastics. It can be fabricated as adamantine or flexible, high- or low-visibility, and fast- or slow-setting. Among common adhesives, epoxy resin is unmatched in heat and chemical resistance. Moreover, the basic requirements of these epoxies used in die bonding could be described as follows: LY556 and HY951 mixing ratio is 10:1. The Composite mixing ratio is 40:60. Epoxy Resin and Hardener have the same Density, Young's Modulus, Poisson's ratio and thermal conductivity which is 1.2g/cc, 3.4GPA, 0.3, 0.188 W/mºC, but Viscosity is 120000 mPAs and 10-20 mPAs for resin and hardener at 25ºC (Figure 2).

Figure 2: Epoxy resin with epoxy hardener

Eggshells are a readily available biowaste product in the food industry. They have high compressive strength and good bonding to the epoxy resin used by researchers. Therefore, researchers selected this material to create the samples. The purpose of NaOH treatment is to improve the mechanical properties of the shell (Figure 3).

Figure 3: Powdered

Eggshells are taken in powdered form at 10 microns and 5 microns. It is prepared by adding 5% NaOH, then drying for 24 hours. It has a Density of 2.11g/cc, Young's Modulus of 10Gpa, and Poisson's ratio of 0.3. Its Ply Dimension is 0.9mm thickness from Sample 2.

3.1. Design Procedure

Researchers use ANSYS 15 to perform the analysis; researchers first design the 2D Surface geometry in ANSYS with the exact dimensions of 3 different samples, then they add material data for Kevlar, epoxy, eggshell, banana spathe, and hair. Using ANSYS ACP-pre, researchers will create material fabrics in which the Thickness of the lamina is entered. The layer orientation of all samples is taken as 0° as per the material Fabrication details on ASTM standards, and layer plots are applied in the Y-direction; then, researchers add material stack-up, orientation, rosettes modelling ply, etc.; finally, from the entered input of sample from 2D geometry, 3D composite models are made. Then, after running the script in ACP-Pre, researchers use static structural components in the ANSYS overview menu. For static structural analysis, mesh refinement is performed to improve the FEA mesh (number of elements per edge) and obtain more accurate results. Finally, researchers use static structural and thermal analysis to solve stress, loads, and support (Figure 4).

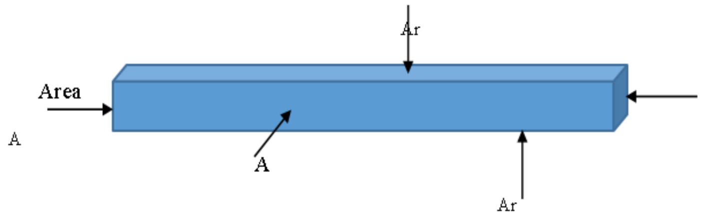


Figure 4: Load and thermal location

4. Results

Hybrid polymer composites will perform better than traditional materials used in the construction of marine bulkheads and ship hulls, where steel or aluminium is more commonly used. Simulations indicate that hybrid composites may weigh up to 60% less than steel while maintaining equal structural integrity. Analysis of stress distribution revealed that the hybrid composites exhibit a good stress distribution, minimising the likelihood of stress concentration in a single area that could lead to failure. Indeed, hybrid composites appear to withstand hydrostatic pressure well and tolerate marine environmental loads without significant deformation or failure. Simulations of impact loads showed that composite materials containing carbon and aramid fibres exhibit high energy absorption, and therefore exhibit greater impact resistance than the glass fibre system. Wave cycles over hybrid composites were simulated for fatigue analysis, revealing slow degradation; therefore, these materials are claimed to be more durable and require less maintenance than conventional materials. Additionally, thermal and environmental degradation simulations confirmed the retention of mechanical properties under high-salinity and temperature-varying conditions, an important advantage for marine applications. Further improvements in the properties can be achieved by optimising the fibre orientation and stacking sequence. Here again, it was proven that the best balance between strength and flexibility is achieved in cross-ply laminates. Hybrid polymer composites can be considered an alternative to conventional materials, offering lightweight, long durability, and anticorrosion properties. Such results support the best fit for modern marine engineering to achieve better performance, fuel efficiency, and sustainability. Hooke's law for orthotropic materials is given as:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{zx}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\epsilon_{xx}\\ \epsilon_{yy}\\ \epsilon_{zz}\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{bmatrix} \quad (1)$$

Stress-strain relationship in composites is:

$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl} \quad (2)$$

Where S_{ijkl} Is the compliance tensor. Finite element discretisation can be framed as:

$$Ku = f \quad (3)$$

Where K is the global stiffness matrix, u is the displacement vector, and f is the force vector. The strain-displacement matrix is given below:

$$B = \frac{\partial N}{\partial x} \quad (4)$$

Where B is the strain-displacement matrix, and N are the shape functions. Element stiffness matrix is:

$$K_e = \int_{\nabla} B^T DBdV \quad (5)$$

Where D is the material property matrix, the energy balance equation is given by:

$$\delta\Pi = \int_{\nabla\sigma} \delta\varepsilon dV: - \int_{\nabla} f\,\delta u dV = 0 \quad (6)$$

Von Mises stress for failure analysis is:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad (7)$$

Natural frequency of a pirate is:

$$\omega = \sqrt{\frac{\pi^4 D}{\rho h a^4}} \quad (8)$$

Where D is the flexural rigidity, ρ is the density, h is the thickness, and a is the length of the plate.

4.1. Comparative Analysis

Once a load is applied to the surface area, the maximum deformation corresponding to the applied stress (max. stress) and the heat flux corresponding to the thermal conductivity are obtained. Thus, the stress, deformation, and heat flux values obtained are entered into the Table and carefully studied. Once a load is applied to the surface area, the maximum deformation corresponding to the stress (max. stress) and the heat flux corresponding to the thermal conductivity are obtained. Thus, the stress, deformation, and heat flux values obtained are entered into the Table and carefully studied. The diagram below provides proof of the deformation of 3 samples under a tensile force of 20KN and the heat flux from thermal analysis, using thermal conductivity at 55ºC, 20ºC, 34ºC, and 60ºC, applied to the assumed walls.

4.1.1. Structural Analysis of Sample 1

Sample 1 of Kevlar and Hair is modelled in 2D, and the layer thickness is specified relative to the material dimensions of each lamina. Loads 10, 12.5, 15, 17.5, and 20KN are applied on the right side of the lamina on the x-axis, and the left side of the x-axis is rigidly supported (Figure 5).

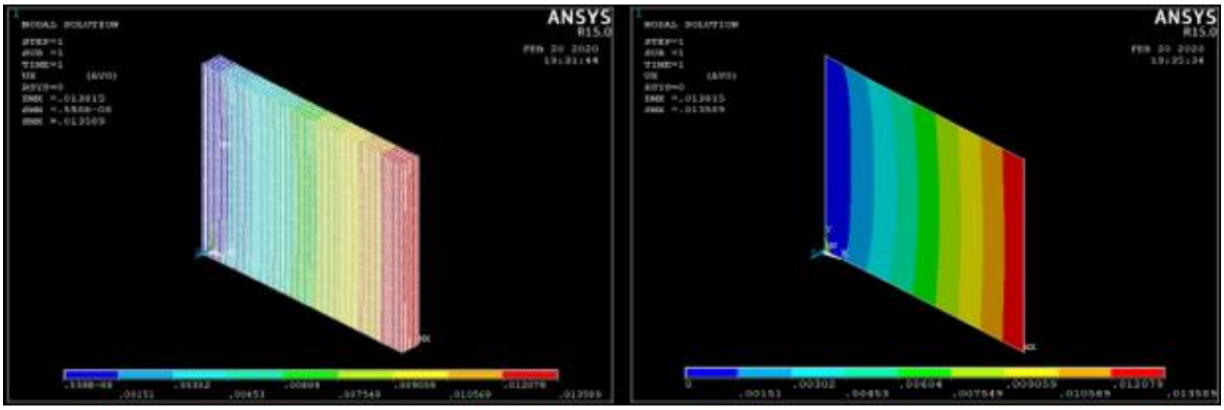


Figure 5: Kevlar and hair analysis (2D and 3D) 10KN

Using FEA, a meshing of small finite elements is done, resulting in the final maximum. Deformation is calculated and observed.

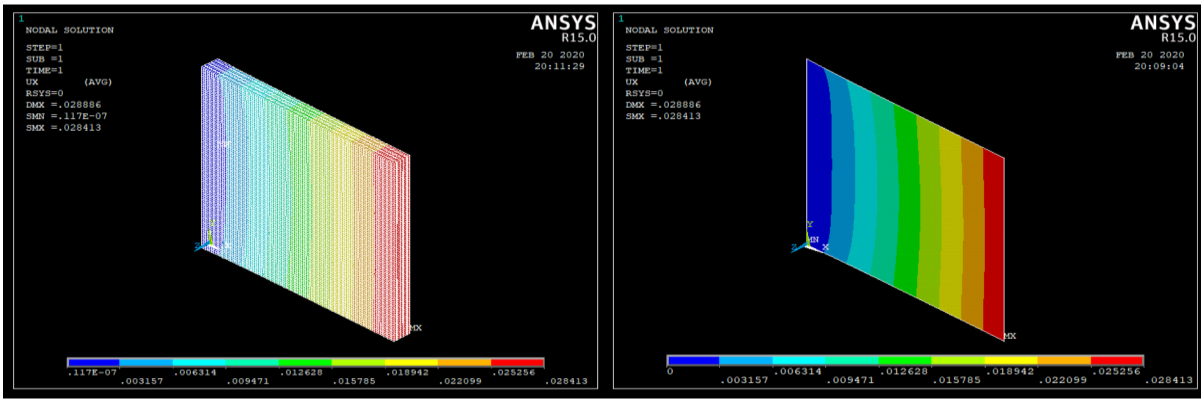


Figure 6: Kevlar and hair analysis (2D and 3D) 12.5KN

Figure 6 shows the deformation of the Kevlar-hair hybrid laminate under a 12.5 kN load. This is shown using both 2D and 3D finite element models.

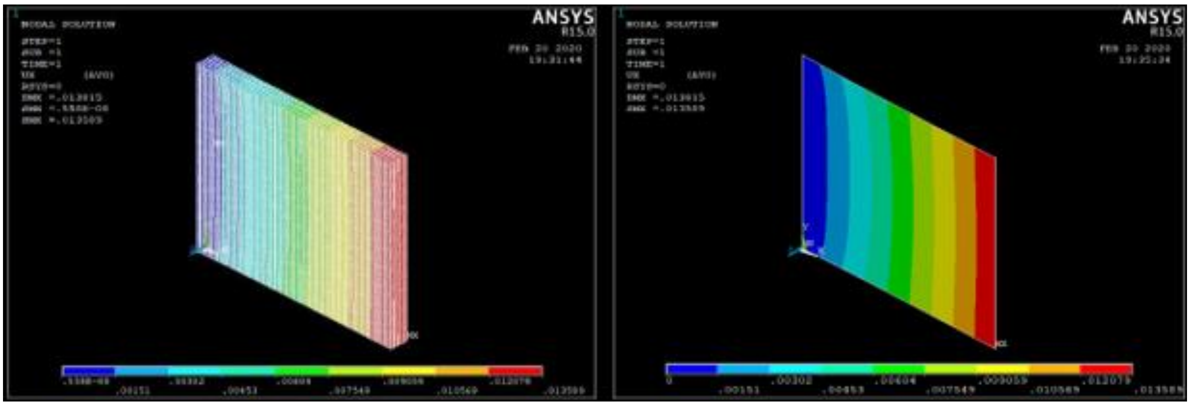


Figure 7: Kevlar and hair analysis (2D and 3D) 15KN

Figure 7 shows how the Kevlar-hair composite reacts to a 15 kN load with better finite element meshing. The results demonstrate a clear increase in deformation near the free end of the laminate, indicating that the structure behaves differently under load, as shown in Figure 7.

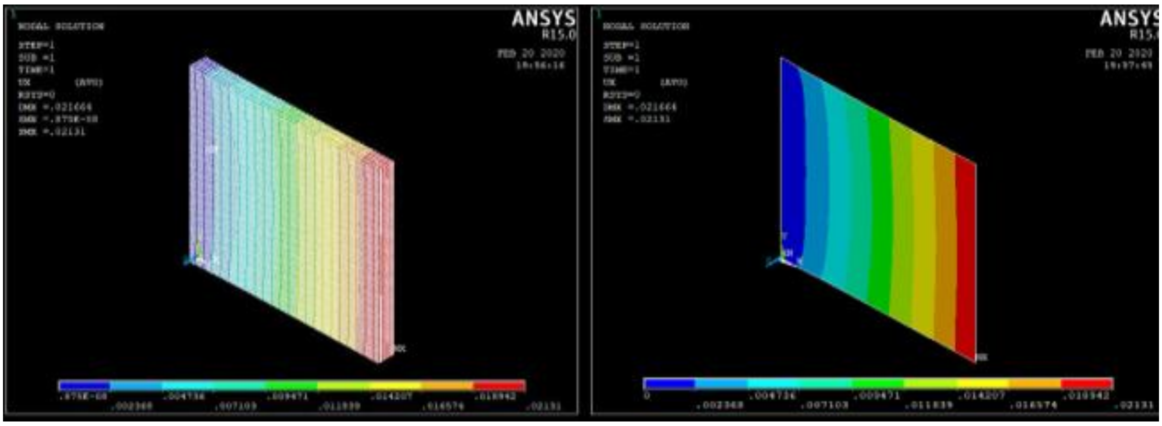


Figure 8: Kevlar and hair analysis (2D and 3D) 17.5KN

Figure 8 shows the 2D and 3D deformation contours of the Kevlar-hair laminate under a load of 17.5 kN. Figure 8 shows that the displacement distribution exhibits a clear trend of increasing deflection with increasing load.

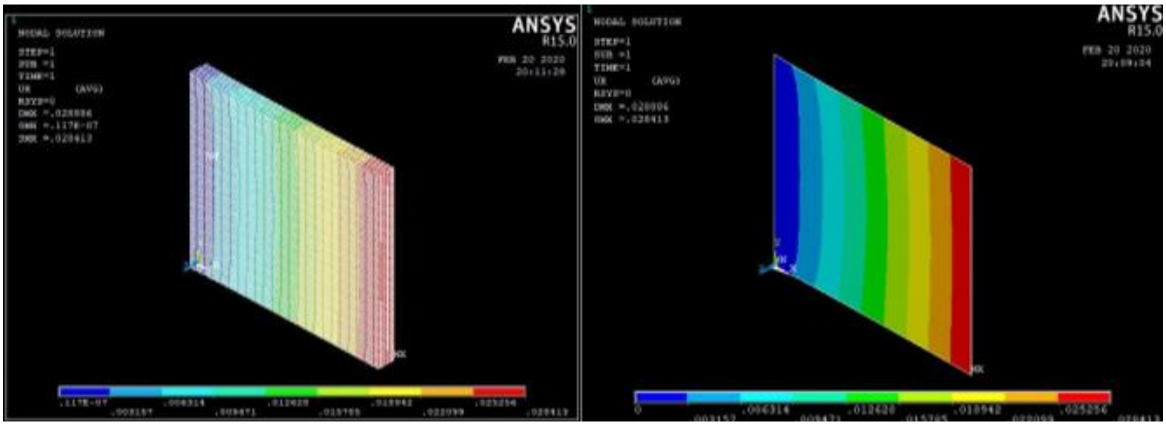


Figure 9: Kevlar and hair analysis (2D and 3D) 20KN

When a 20 kN load is applied to the Kevlar-hair hybrid composite, Figure 9 shows the maximum bending it can withstand. This figure shows the maximum displacement levels for all load situations, indicating the upper deformation range of the laminate, as shown in Figure 9.

4.1.2. Structural Analysis of Sample 2

Sample 2 of Kevlar and Eggshell is designed in 2D, and the layer thicknesses are specified with respect to the material dimensions of each lamina.

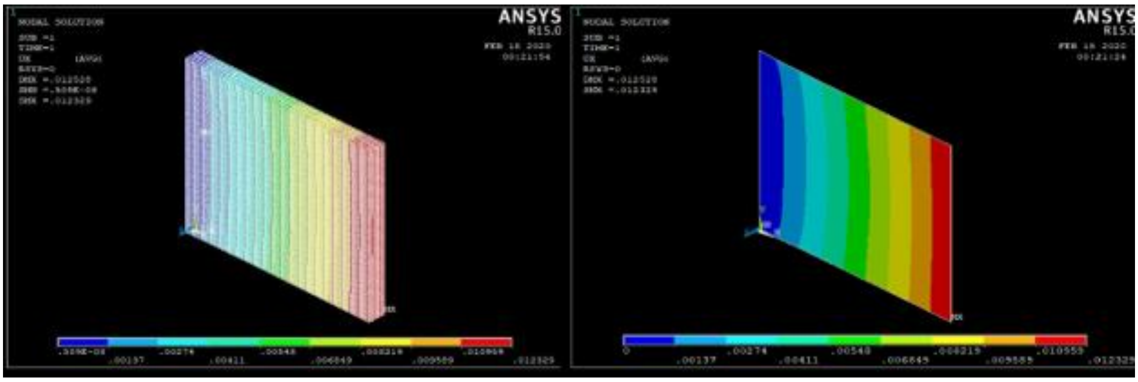


Figure 10: Kevlar and eggshell analysis (2D and 3D) 10KN

Figure 10 shows the 2D and 3D finite element deformation results of the Kevlar–eggshell hybrid laminate when a 10 kN load is put on it. Figure 10 shows that the contour plots indicate homogeneous deformation and effective load transfer throughout the laminate thickness.

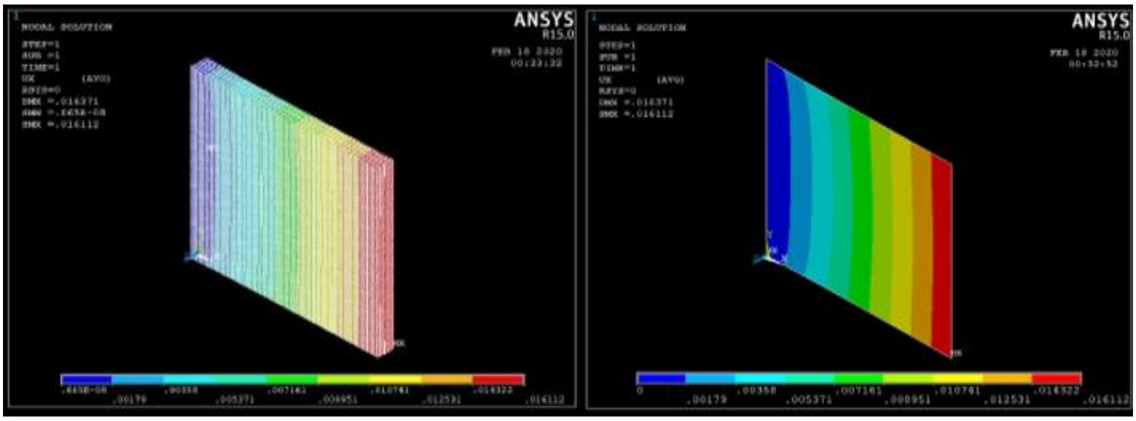


Figure 11: Kevlar and eggshell analysis (2D and 3D) 12.5KN

Figure 11 shows the 2D and 3D finite-element deformation results for the Kevlar–eggshell hybrid laminate under a 12.5 kN load. Figure 11 shows that the contour plots exhibit a smooth displacement gradient from the fixed edge to the free edge. This means that the load is stable over the thickness of the laminate.

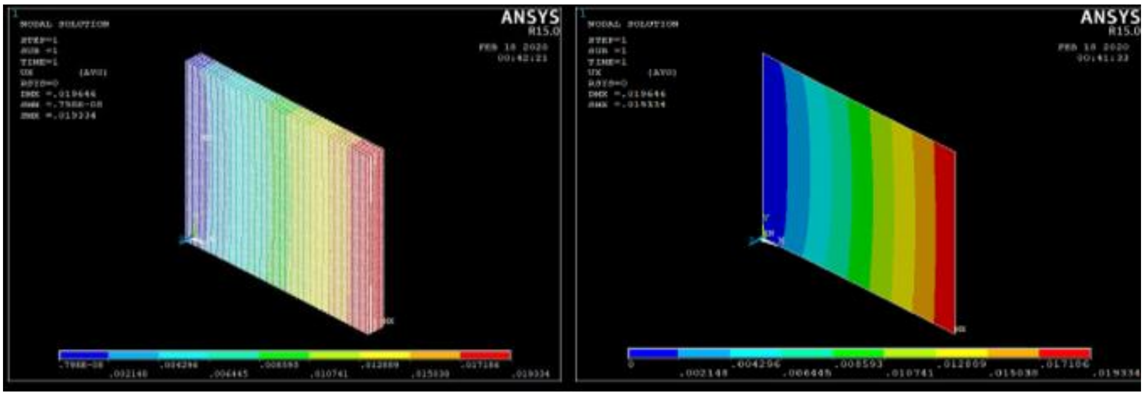


Figure 12: Kevlar and eggshell analysis (2D and 3D) 15KN

Figure 12 shows how the Kevlar–eggshell composite changes shape when a 15 kN load is applied to it. This is done using enhanced finite element meshing in both 2D and 3D. Figure 12 shows that the maximum deformation has increased, but the overall pattern of deformation has remained the same.

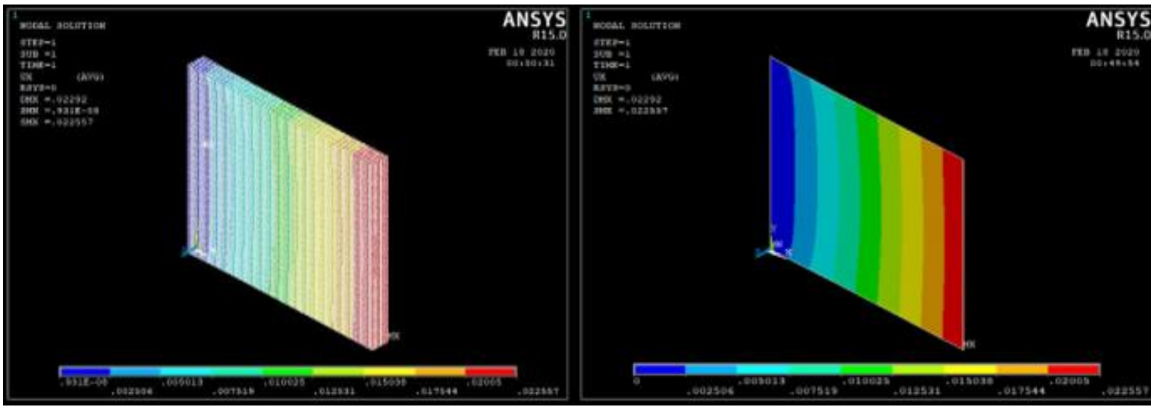


Figure 13: Kevlar and eggshell analysis (2D and 3D) 17.5KN

Figure 13 shows how the Kevlar–eggshell hybrid laminate reacts structurally when a 17.5 kN load is put on it. The displacement contours show that the deflection is greater closer to the free end, which supports the idea that more load causes laminate deformation, as seen in Figure 13.

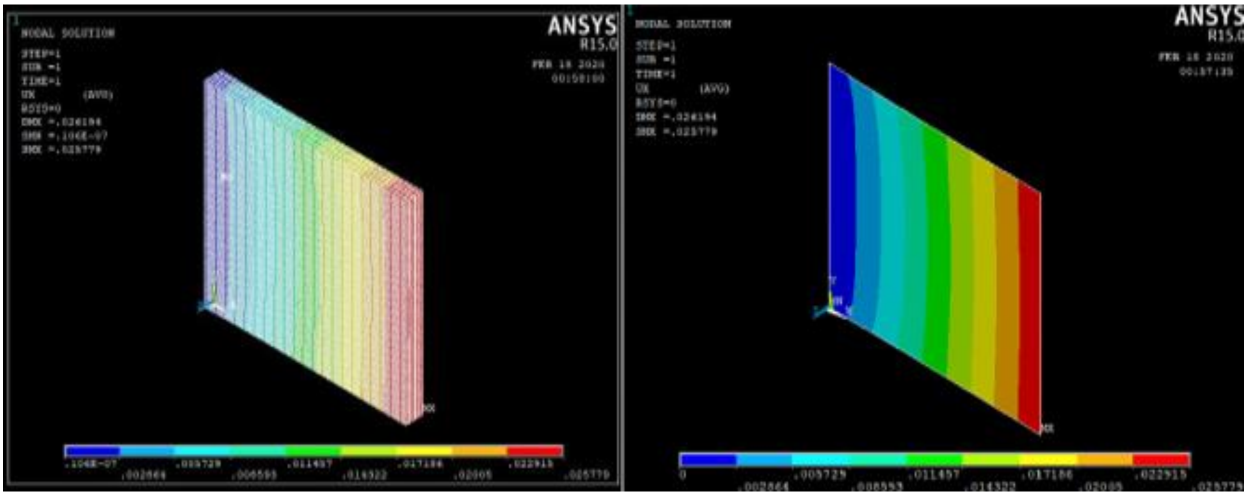


Figure 14: Kevlar and eggshell analysis (2D and 3D) 20KN

Figure 14 displays the 2D and 3D finite-element deformation contours of the Kevlar–eggshell hybrid laminate under a 20 kN load. As shown in Figure 14, the maximum deformation condition for the eggshell-reinforced laminate exhibits a clear displacement gradient across the structure.

4.1.3. Structural Analysis of Sample 3

Sample 3 of Kevlar and Banana Spathe is modelled in 2D, with layer thickness specified relative to the material dimensions of each lamina. Loads 10, 12.5, 15, 17.5, and 20KN are applied on the right side of the lamina on the x-axis, and the left side of the x-axis is rigidly supported by using FEA meshing of a small finite element—the final maximum. Deformation is calculated and observed.

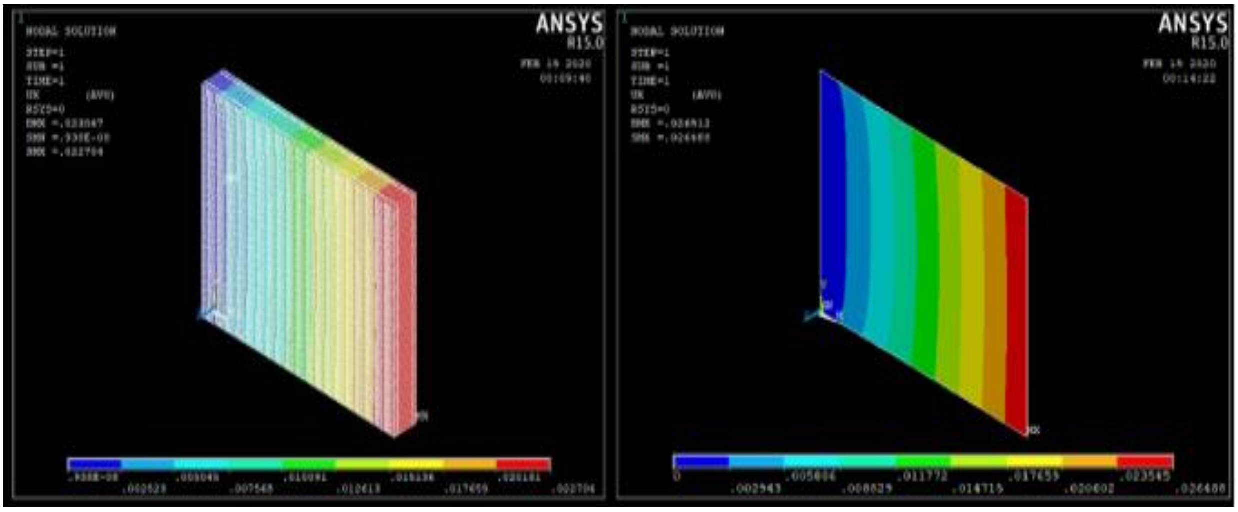


Figure 15: Kevlar and banana spathe analysis (2D and 3D) 10KN

Figure 15 shows the 2D and 3D deformation results for the Kevlar-banana spathe hybrid laminate under a 10 kN load. The contour plots reveal that the laminate deformed and the stress was evenly distributed, indicating how this hybrid composite first responded structurally, as seen in Figure 15.

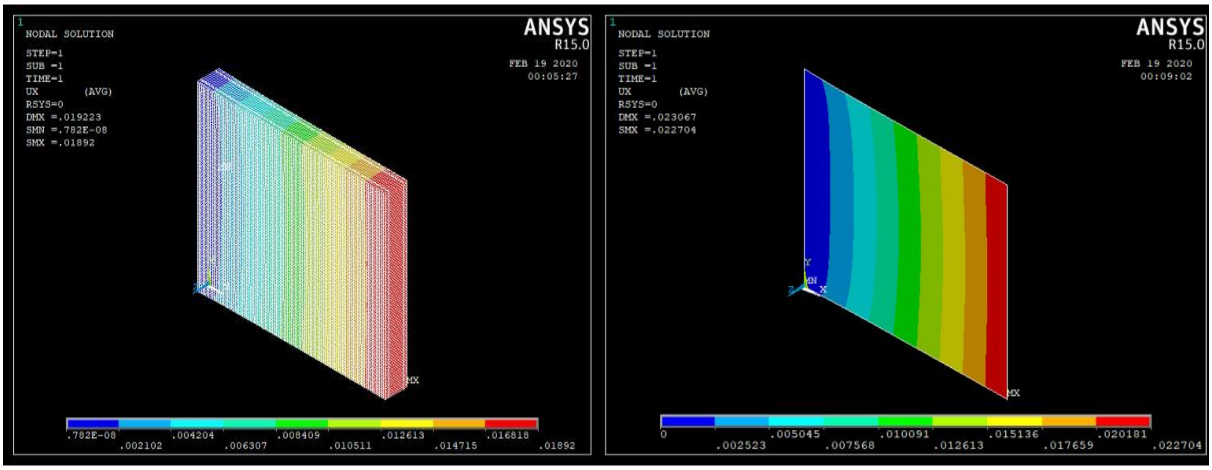


Figure 16: Kevlar and banana spathe analysis (2D and 3D) 12.5KN

Figure 16 shows the 2D and 3D finite-element deformation results for the Kevlar–banana spathe hybrid laminate under a 12.5 kN load. The contour plots in Figure 16 demonstrate that the displacement increases slowly from the fixed edge to the free edge. This means that the structure behaves stably under moderate stress.

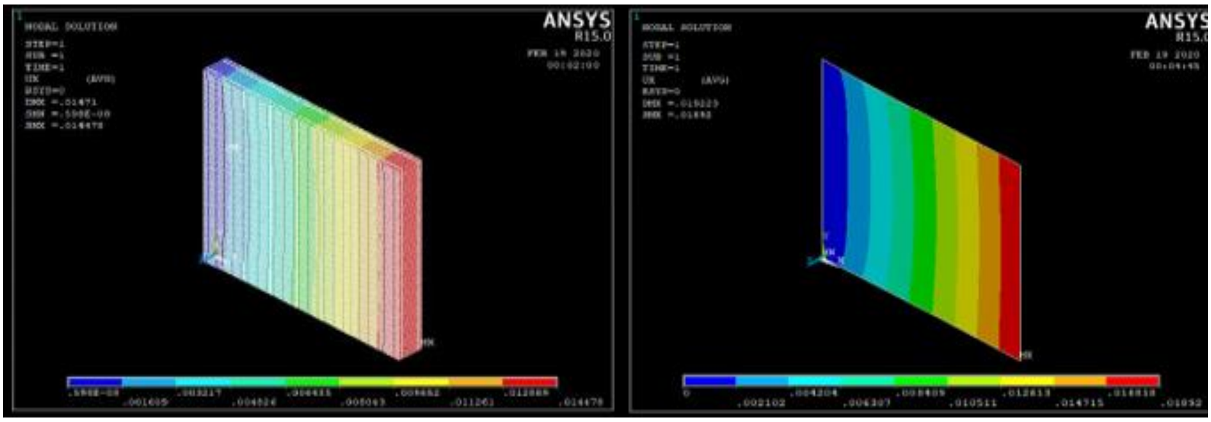


Figure 17: Kevlar and banana spathe analysis (2D and 3D) 15KN

Figure 17 shows how the Kevlar-banana spathe composite changed shape under a 15 kN load. This was done using both 2D and 3D finite element analysis. The results show that the maximum deformation has increased while the deformation pattern across the laminate has stayed the same, as shown in Figure 17.

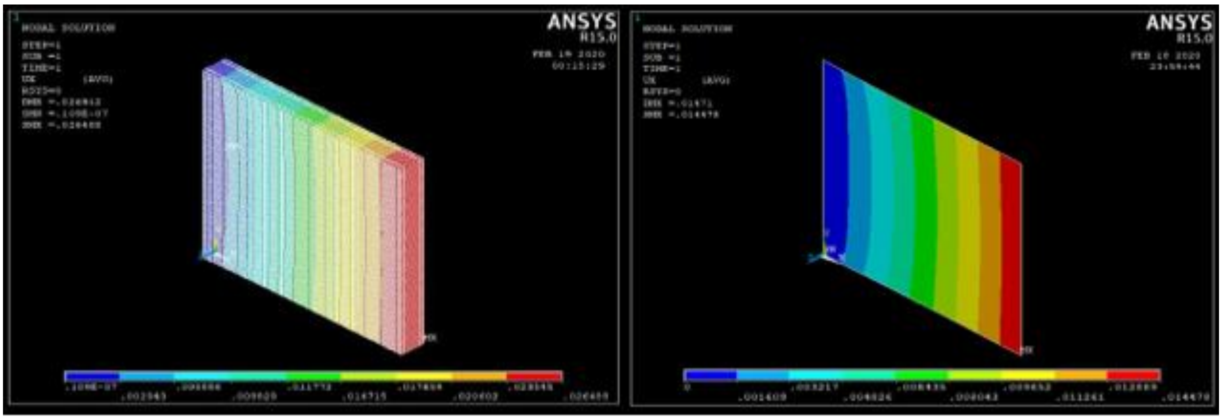


Figure 18: Kevlar and banana spathe analysis (2D and 3D) 17.5KN

Figure 18 shows how the Kevlar–banana spathe hybrid laminate reacts to a 17.5 kN load. The displacement contours indicate that deflection is greater near the free end, demonstrating how the load affects the composite structure (Figure 18).

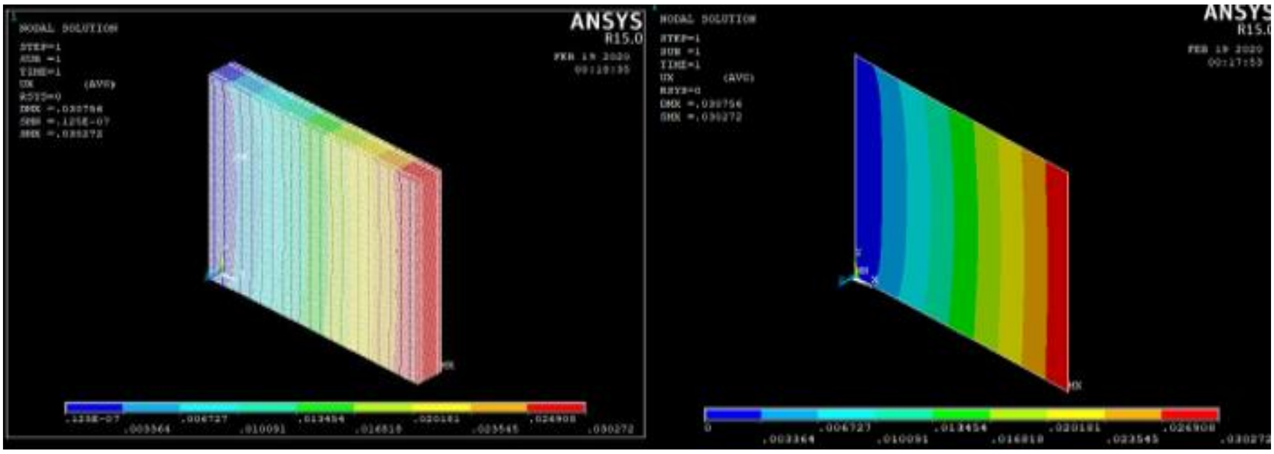


Figure 19: Kevlar and banana spathe analysis (2D and 3D)

Figure 19 displays the 2D and 3D finite element deformation contours of the Kevlar–banana spathe hybrid laminate under a 20 kN load. This image shows the maximum deformation that can occur in this composite system, which exhibits a clear displacement gradient across the laminate.

Table 3: Determination of maximum deformation

Load (Kn)	Max. Deformation (Mm)		
	Def. of Sample 1 (Mm)	Def. of Sample 2 (Mm)	Def. of Sample 3 (Mm)
10	0.013589	0.012329	0.014478
12.5	0.017758	0.016112	0.01892
15	0.02131	0.019334	0.022704
17.5	0.024862	0.022557	0.026488
20	0.028413	0.025779	0.030272

Table 3 shows the maximum deformation values for Samples 1, 2, and 3 when loads of 10-20 kN were applied. The findings clearly reveal that Sample 2 consistently exhibits the least deformation across all load scenarios, indicating that it is stiffer than the other samples, as shown in Table 3.

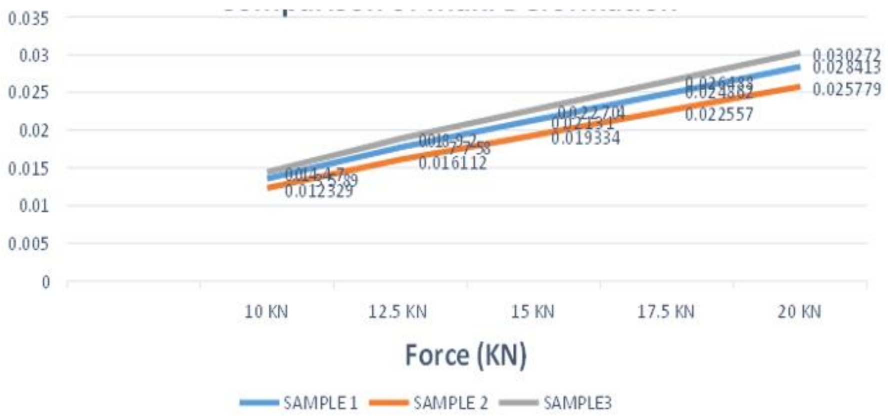


Figure 20: Comparison of max deformation

From Figure 20, the researchers found that sample 2 had the lowest deformation at all loads. Sample 1 lies above sample 2 but below sample 3. Sample 3 experienced more deformation than the rest of the sample. Hence, researchers conclude that the tensile strength of sample 2 (Kevlar-29 + eggshell) is higher than that of the other two samples.

4.1.4. Thermal Analysis of Sample 1

After structural analysis, Sample 1 is transferred to the thermal method. Here, the dimensions and Thickness are all the same as those used in the structural method. The ambient temperature is 34ºC, and the top, bottom, and left-side layer temperatures are 55ºC, 20ºC, and 60ºC, respectively. The heat flux corresponding to thermal conductivity and temperature is observed (Figure 21).

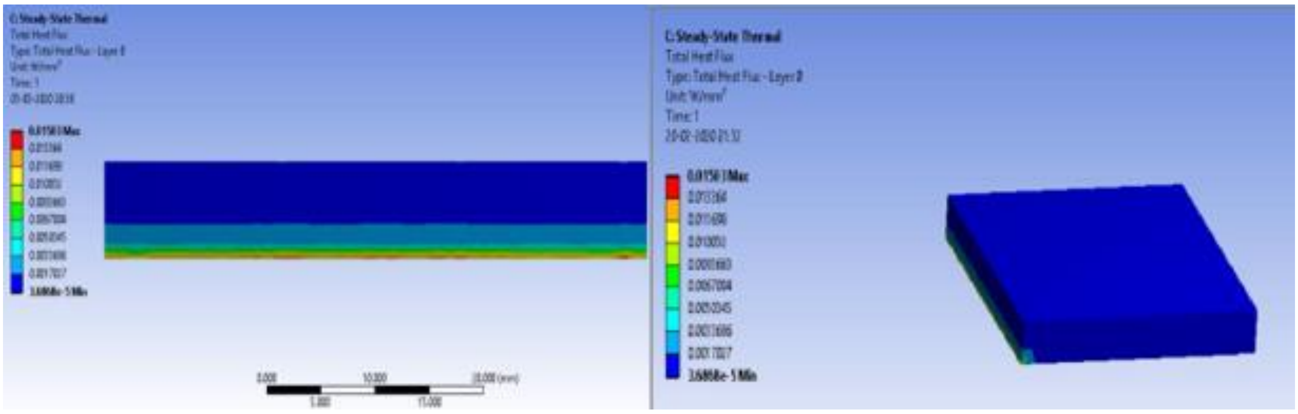


Figure 21: Kevlar and hair analysis (2D and 3D)

4.1.5. Thermal Analysis of Sample 3

Sample 3 is analysed in accordance with the concepts outlined in the above method. The ambient temperature is 34ºC, and the top, bottom, and left-side layer temperatures are 55ºC, 20ºC, and 60ºC, respectively. The heat flux corresponding to thermal conductivity and temperature is observed (Figure 22).

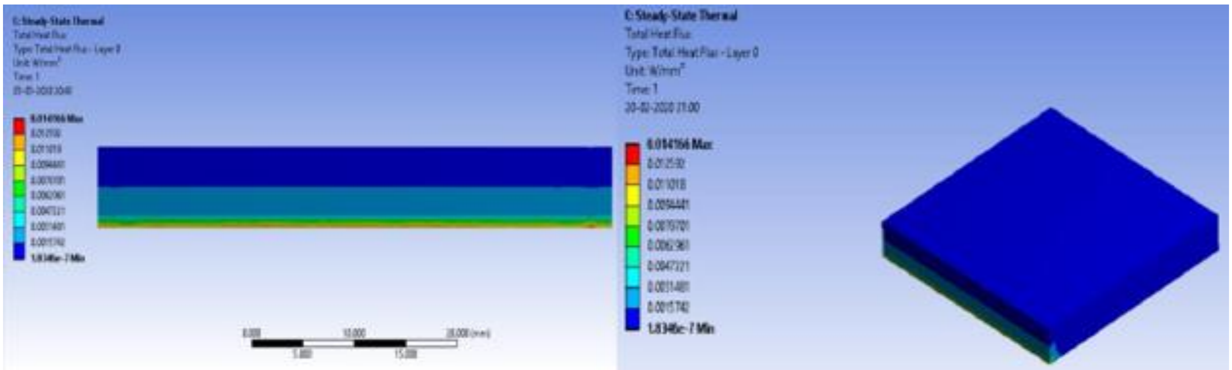


Figure 22: Kevlar and banana spathe analysis (2D and 3D)

Table 4 shows the thermal conductivity and heat flux figures for three composite samples. The data show that Sample 2 has the largest heat flux and Sample 3 has the lowest. This means that Sample 2 is better at retaining heat.

Table 4: Determination of heat flux

No.	Sample	Thermal conductivity (W/mK)	Heat Flux (W/mm^2)
1	Sample 1	0.174	0.01503
2	Sample 2	0.227	0.019608
3	Sample 3	0.164	0.014166

Plotting the value obtained in Table 4 with our best assumption of 2D axes. Sample 2 shows an increase in thermal conductivity and heat flux. Sample 3 has lower conductivity and heat flux than the other two samples. Sample 3 is slightly similar to sample. Researchers observed that sample 3 has better resistance to heat radiation due to its lower conductivity and heat flux (Figure 23).

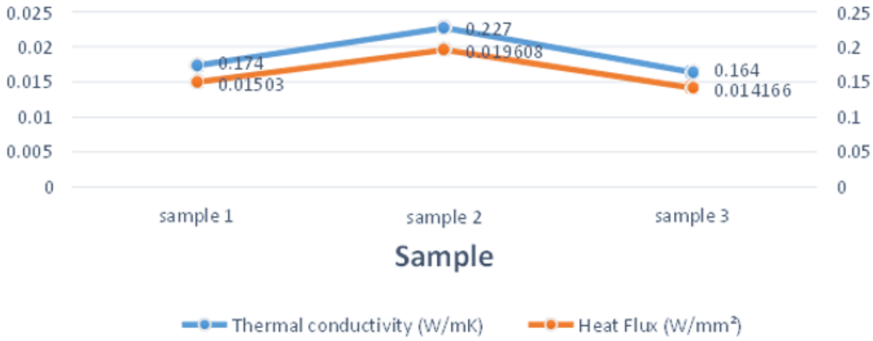
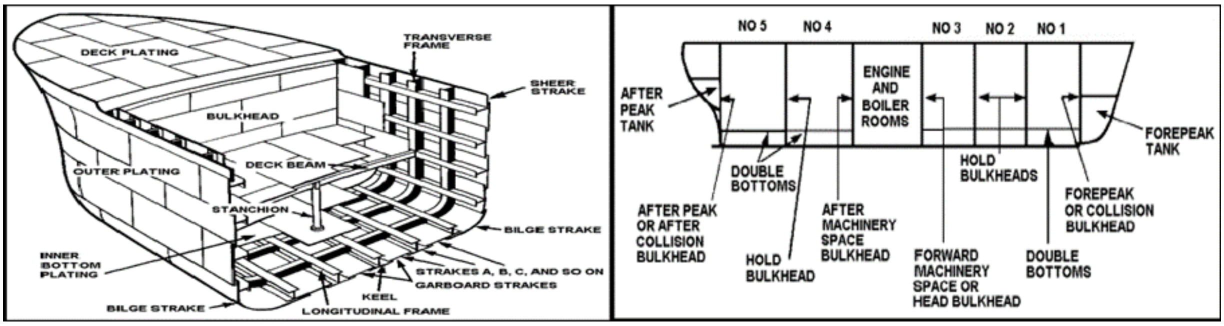


Figure 23: Comparison of the heat flux of samples

4.2. Application

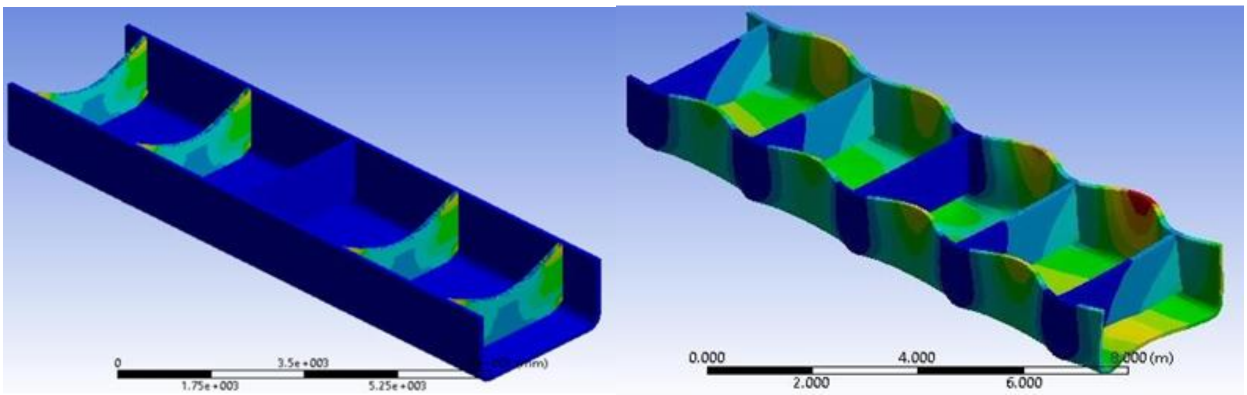
4.2.1. Application in Bulkhead

The final polymer composite sample (Sample 2) is employed in the bulkhead of the ship. Based on modern ship dimensions, the loads are applied to locations that resist deformation. For collision buckling and ship weight, the load is applied on horizontal and vertical components, especially in the negative direction of the side wall. From the figure, it is understood that the ship has many types of bulkheads on its hull body, i.e., five bulkheads. It is assumed that the load applied is 2e6 N. The design is done in SOLIDWORKS and imported into ANSYS ACP Pre to create a composite solid using material fabrics, material stack-up, rosette direction and orientation sets, and finally, solid models. Our composite bulkhead has 20 items arranged to support heavy loads. The ship bulkhead and type of deforming body are mentioned in the figure below. The green and red colours indicate the loading (Figure 24).



Ship structure

Bulkhead location in ships



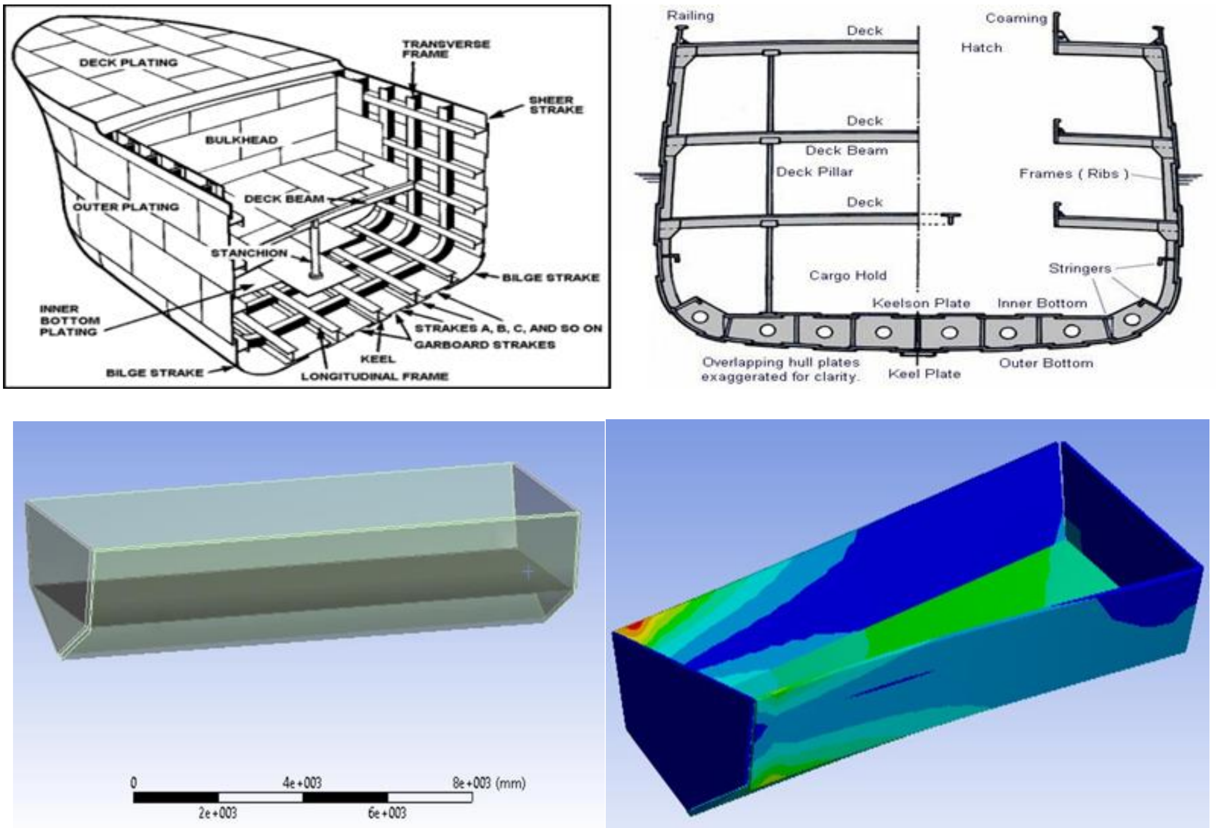
Ship weight Loading

Collision Loading Fig

Figure 24: Analysis of bulkhead

4.2.2. Application in Ship Hull

Similar to the bulkhead, the final polymerised composite from Sample 2 is used in the ship's hull due to its high compressive strength. By assumption of ship dimension, the loads are applied to parts of the hulls such that the main deformation must be eliminated.



Before Loading After Loading

Figure 25: Analysis of the ship hull

Figure 25 shows the hull location in ships. The design and material creation are done using SOLIDWORKS and ANSYS ACP pre-import.

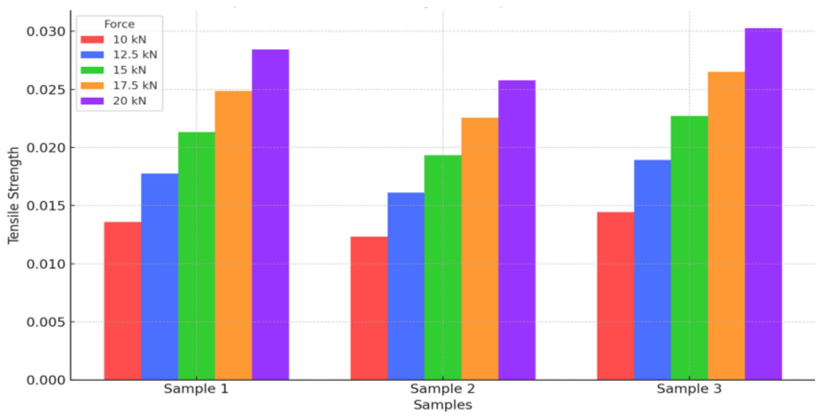


Figure 26: Variation of tensile strength for different samples under varying applied forces

With the help of material fabrics, material stack-up, rosette direction, and orientation sets, solid models are finally created. The loads are applied at the hull's face to resist deformation. The deformed loads are observed. The hull composites are produced in limited quantities to free up space for high-strength ships. A greater number of stacking items can protect the hull. But researchers use a few stack items, as in commercial ships. Figure 26 gives the tensile strength values of three samples, Sample 1, Sample 2, and Sample 3, at five applied force levels, 10 kN, 12.5 kN, 15 kN, 17.5 kN, and 20 kN. For example, every bar in a set represents the tensile strength at a given level of force. All samples exhibited a consistent, proportional increase in tensile strength with increasing force. This was obtained from the graph results. Forces are presented as red for 10 kN up to a colour-coded purple for 20 kN. Thus, based on the trend from the graphs, there appears to be a positive correlation between tensile strength and the applied forces. In general terms, sample 3 shows the maximum tensile strength at each corresponding force level. Although it gave about 0.030 at 20 kN, this was still suggestive of better material properties or greater structural strength. It is only second to Sample 2, with tensile strength values slightly below. The sample with the least tensile strength is Sample 1. This was always recorded low and never peaking above 0.028 at 20 kN. This indicates a uniform trend across samples; the material behaves consistently as force increases, whereas variations among samples suggest differences in composition or structure. This tensile-strength comparison across samples and levels of force would provide significant information on the material's behaviour and suitability for high-mechanical-strength applications.

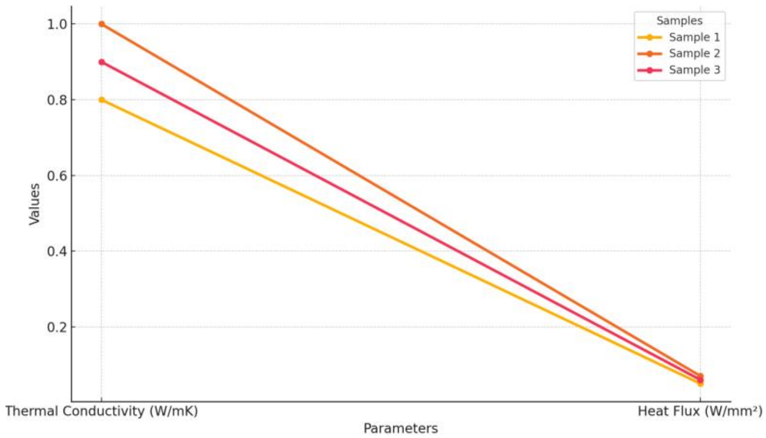


Figure 27: Structural and thermal analysis result

Figure 27 represents the Heat flux (W/mm²) vs. thermal conductivity (W/mK) for Sample 1, Sample 2 and Sample 3. The left axis is assigned to thermal conductivity, and the right to heat flux. For easy comparison, a trend line describing all samples and relevant markers is plotted. The highest thermal conductivity was measured for Sample 2 at 1.0 W/m·K. The second would be Sample 3 at 0.9 W/mK, then Sample 1 at 0.8 W/mK. This would make Sample 2 the most efficient in transferring heat. In terms of heat flux-that is, the flow of heat per unit area-Sample two is leading the pack, followed closely by Sample 3, then Sample 1, at respective rates of 0.07, 0.06, and 0.05 W/mm². All of the lines relating thermal conductivity to heat flux slope downward; that is, a consistent pattern: the larger the thermal conductivity, the larger the heat flux for all three samples. This shows that materials with higher thermal conductivity dissipate heat more readily. This graph well illustrates how each sample performs in terms of relative thermal properties; from this, Sample 2 has outperformed the rest, including the parameters, while Sample 1 lags behind. This visualisation does well to compare thermal performance metrics and open up insights into material suitability for heat transfer applications (Table 5).

Table 5: Cost estimation

No.	Description	Cost (In Rupees)
1	Sample Fabrication	10,000
2	Thermal Conductivity Test	5,200
3	Software/Tool Design	16,000
4	Other (Indirect Expense)	3000
5	Total Cost (Rs)	34,200

5. Result and Discussion

There were conventional steel-based ship hull materials that served the needs at the construction stage, but came with significant disadvantages; their heavy weight caused inefficiencies in the functionality of marine vehicles, as increased weight reduced speed. Poor manoeuvring of the vessels, along with their weight, makes them more fuel-inefficient and heavier themselves. In addition, it exhibits low impact absorption. Thus, it is highly susceptible to external influences that may compromise its structural integrity in the event of impacts or harsh sea conditions. It tends to cause submerging conditions in the vessels and their residents. Steel does not fare much better in terms of weight; it tends to make matters worse. This composite material is Kevlar. It has proved to be the best possible alternative for meeting the battle plan to overcome the challenges, mainly because of its superior strength-to-weight ratio and impressive impact resistance and flexing. Strategic placement within the hull provides optimal support while reducing overall weight and protecting against external forces. This invention will overcome the disadvantages of steel by enabling the hull to withstand very stringent marine conditions. Using steel for bulkheads has several disadvantages. Steel bulkheads weigh heavily. Such makes the ship heavy. Heaviness thus makes fuel consumption much less efficient. During this time, when marine operations should be environmentally friendly and cost-effective, inefficiencies are detrimental. It would make the ships substantially lighter by replacing steel in the bulkheads with Kevlar composite material. Hence, fuel ingestion decreases, and operational performance improves. Kevlar provides structurally sound bulkheads with a great strength-to-weight ratio, but absorbs much less energy for propulsion. Besides, Kevlar has properties that make it resistant to corrosion and wear. Therefore, Kevlar is an excellent candidate for marine applications, as saltwater and extreme weather conditions are common in marine environments. To demonstrate the advantages of the Kevlar composite material over steel, experimental analyses were conducted.

The data received was graphically represented. This graphical representation furnished a clear outlook of the output. From the line-stacking chart, deformation trends under various loading conditions can be depicted in an example graph as a function of force. The plot shows how the materials respond to the applied forces. The prepared graphs include force versus stress and thermal conductivity versus heat flux, with mechanical and thermal properties measured, respectively. These graphs have revealed Kevlar's superiority in both structural and thermal properties. From the data analysis, the following important findings were obtained: Initially, the samples prepared with the composite material Kevlar had lower stress and deformation values than those prepared with steel. This resulted in higher tensile and flexural strengths for Kevlar, enabling it to withstand greater mechanical loads without compromising structural integrity. Thermal conductivity and heat flux values for Kevlar were much lower than those for the steel samples, further evidence of Kevlar's very good resistance to heat. Such a property is highly advantageous in marine applications, as extreme temperatures significantly affect the performance and durability of materials. Kevlar is the best because it has high mechanical strength and low thermal conductivity, making it suitable for use in the crucial parts of marine vessels, including bulkheads, hulls, superstructures, and rescue boats. The study was closely related to deformation, stress, and heat flux across samples.

It concluded the study by providing a final assessment of what may be an ideal material for marine applications. Kevlar reduces weight without sacrificing strength or durability, which directly addresses the core issues associated with steel. Lighter weight improves fuel efficiency and enhances the vessel's manoeuvrability and performance. And Kevlar's much higher impact resistance ensures that hull and bulkheads are much more resistant in the toughest marine conditions than any other material, further enhancing its safety by preventing damage to the vessel and its occupants. Additionally, Kevlar has lower thermal conductivity. This makes it reliable to some extent; its impact on the part that might endure this heat effect on or in the ship will further increase its lifetime. The most significant development in marine engineering has been the shift from steel to a Kevlar composite. Kevlar is a material whose specific structure is to be lightweight while maintaining high mechanical strength and heat resistance. It can thus be used for all applications related to marine systems, including, but not limited to, bulkheads and hulls, superstructures, and rescue boats. This research work has produced results that will only reinforce the grounds for the use of Kevlar in marine environments, while offering full proof of how it might revamp the techniques and designs behind shipbuilding. This would therefore offer higher efficiency and sustainability, with much greater safety, in Kevlar. In fact, with this, a new era of maritime technology development will begin for the next generation.

6. Conclusion

The analytical graphs show that sample 2, which is made of Kevlar-29 reinforced with powdered eggshell, has the highest tensile strength of all the samples examined. This improved mechanical performance is due to its higher Young's modulus, which makes it stiffer and able to withstand high pressure and mechanical stresses without changing shape. The results clearly show that powdered eggshells can be used as a reinforcement material to strengthen structures. This discovery shows that using cheap, eco-friendly waste materials like eggshells in sophisticated composite applications that require better mechanical properties is possible. The thermal study, on the other hand, demonstrates that sample 3 has better thermal resistance than the other samples. The main reason for this better thermal behaviour is its lower thermal conductivity and lower heat flow. These traits show that sample 3 is better at preventing heat transfer, making it better for applications where thermal insulation is very important. Because of this, sample 3 is highly recommended for use in places with high temperatures, such as ship coal chambers or areas where seawater is quite hot in the summer. It makes things safer and more energy-efficient in these extreme thermal conditions by limiting heat flow. When choosing materials for marine structures, the application requirements are particularly important. Sample 2 is the best choice for bulkhead and hull structures because it has better tensile properties, is stronger, and can hold more weight. Sample 3, on the other hand, has clear advantages where thermal resistance is the most important factor. Sample 2 has a slightly lower thermal resistivity, as shown by slightly higher thermal conductivity and heat flux values (changing by just ±0.05). However, these changes are not very big. Overall, the results show the importance of balancing mechanical strength and thermal performance when choosing composite materials for specific technical applications. This will ensure the materials work well and last a long time.

6.1. Future Scope

Accuracy in the measurement of techniques of stress, strain, Poisson's ratio, and Young's modulus in the y and z directions shall be increased to ascertain reliability in assessing mechanical properties. Optimising performance depends heavily on accuracy in specialised applications, so measurements of such precision become relevant. This research focuses more on orientation and changing orientation, so Kevlar and other composite materials, which might produce an overall strengthening effect. Higher load-bearing capacity and durability can be achieved by properly adjusting fibre alignment and the composite structure. The conventional technique for the method in preparation of materials - the hand layup technique - would also impose limitations on uniformity and properties in the material. The proposed transition in the manufacturing process aims to improve uniformity and precision, and to enable repeatable fabrication of composite materials. To ensure that all materials under study are well understood, each component is tested individually to determine its key mechanical and thermal properties. Detailed characterisation is followed by comprehensive analyses that assess the overall performance of composite materials and their suitability for specific applications. Collectively, these initiatives will lead to robust methodologies and fabrication practices that yield optimal strength, accuracy, and reliability in Kevlar-based composite materials for high-performance structural applications.

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Conflicts of Interest Statement: The authors declare that there are no conflicts of interest associated with this work, and all sources used have been appropriately cited.

Ethics and Consent Statement: Ethical approval was obtained prior to the study, and informed consent was secured from the participating organizations and individuals involved in the data collection process.

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