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Numerical Investigation of Bamboo, Horsetail, and Cattail Structures for Enhanced Mechanical Performance for 3D Printing

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Abstract: Biomimetic design is motivated by nature to enhance engineering solutions, providing strategies to develop structures minimized in weight, maximized in strength, and optimized for efficiency. Plants such as bamboo, horsetail, and cattail stand out as notable examples because of their nature-refined geometries. Whereas their potential has been acknowledged, there has been inadequate research into how these designs function under real mechanical stresses. In this study, the strength, stiffness, and deformation of bamboo-, horsetail-, and cattail-inspired structures have been studied under dynamic compression with the help of ANSYS Workbench simulations. The 3D models were developed in CATIA and analysed using two materials, which are PLA and ABS. Results stated that PLA usually performed better with respect to strength. Among all the designs, the horsetail H-07 model stood out with the maximum stiffness and load-bearing capacity because of its well-placed internal stiffeners. Bamboo B-03 and cattail C-03 models also displayed resilient performance, while not attaining the level of the horsetail structure. These findings focus on the tangible benefits of nature-inspired engineering, especially for additive manufacturing (AM). With thoughtful selection of materials and optimising bioinspired designs, engineers are able to develop lightweight yet reliable components for an extensive range of applications.

Keywords: *Biomimetic Structures, 3D Printing, PLA, ANSYS Simulation, Mechanical Strength.*

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I. INTRODUCTION

Biomimetics, otherwise known as biomimicry or bio-inspired design, is the discipline of acquiring understanding Nature-driven engineering approaches and Tech-related difficulties. The term Traces back to the Based on Greek etymology “bios”, meaning life, as well as “mimesis”, meaning imitation combined in describing the replication of natural systems, processes, and techniques to develop practical solutions [1]. A factor contributing to the significance of biomimetics is its foundation in evolution: over many millions of years, plants and animals have formed frameworks and processes that are highly efficient, resilient, and modifiable.

Contrary to conventional engineering approaches, which often depend on simple or linear techniques, biomimetic design focuses on functional diversity, resource efficiency, and durability over time. Instances are found widely, from the manner in which bird wings have prompted aircraft design to how the lotus leaf has resulted in the development of self-cleaning surfaces. Through the unification of the natural system–derived understanding with modern science, biomimetics is promoting advances across domains such as structural engineering, robotics, renewable energy, and healthcare.

A significant attribute of biomimetic design derives from its natural alignment with sustainability. Through inspiration from biological procedures and structures, engineers can implement solutions that acquire fewer resources, function more efficiently, and reduce waste generation. Nature provides an extensive range of examples of this optimisation: plant stems, insect wings, and seashells all feature elaborate yet effective designs that provide high strength while maintaining weight to a minimum [2]. These fundamentals have steered the development of lightweight but tough materials that are currently finding use in areas such as aerospace, automotive engineering, and construction.

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The merging of biomimetic ideas with advanced manufacturing techniques, mainly additive manufacturing (AM), has extended the range of opportunities. This collaboration between nature-inspired design and progressive fabrication makes possible the production of complex geometries, modifiable materials, and sturdy structures that would have been very demanding or even impossible to attain with the help of traditional techniques. In this process, biomimetics not only supports progress in technological innovation but also instills an environmentally conscious insight into the development of future engineering solutions.

- *Additive Manufacturing and Biomimetics*

Additive manufacturing (AM), widely accepted as 3D printing, marks a significant technological advancement that transforms digital 3D models into hands-on objects by building them layer upon layer [3]. As opposed to standard subtractive methods or molding a technique, AM allows the fabrication of highly sophisticated designs without being limited by tooling or machining constraints. This results in them being especially apt for biomimetic applications, as many natural structures, namely the porous network of bones or the complex vein patterns in leaves, exhibit geometries that can be directly replicated through AM.Apart from its ability to reproduce such biological complexity, AM offers main advantages, such as minimised material use, high design flexibility, regional production, and quick prototyping. Such features have established it as an essential tool in sectors such as aerospace, medical engineering, and defence. Moreover, its coordination with sustainable practices further enhances its function as an eco-friendly technology by reducing the energy usage and production of waste [4].AM originated as a prototyping tool but has subsequently advanced into an established method for developing fully functional components. It is now applied across a wide range of industries, from lightweight lattice structures for aircraft to patient-orientated medical implants and collision-resistant automotive parts derived from natural designs [5]. The integration of biomimetic principles into AM has altered the potential of this technology, resulting in the development of effective, high-performance structures. Examples include bio-inspired lightweight designs manufactured with advanced polymers and metals, which demonstrate remarkable strength-to-weight ratios compared to traditional parts. With ongoing developments in multi-material printing and responsive smart materials, the scope of AM continues to widen. These advancements make it possible to engineer components with customised mechanical, thermal, and electrical properties [6]. Through the merging of biomimetics and AM, a prominent pathway has emerged that not only encourages technological boundaries but also facilitates environmentally responsible innovation.

II. LITERATURE REVIEW

The working toward better crash safety and energy absorption in lightweight structures has supported the research into bio-inspired multi-cell tubes as an alternative to conventional circular tubes. [7] stated that partitioning a single circular tube into various smaller cells enhances energy absorption by achieving uniform force distribution upon impact. Based on insights from biological systems namely plant stems and bone tissues, researchers have continued to develop multi-cell designs that emulate these natural patterns. Such configurations not only increase structural robustness but also facilitate superior crash performance [8]. Such developments offer substantial potential for generating safer, impact-resistant structures in areas including disciplines such as automotive, aerospace, and civil engineering.

- *Bamboo*

Bamboo has grown to be a prominent model in bio-inspired design due to its remarkable stiffness-to-mass ratio, demonstrating superior performance compared to metals such as steel and aluminium [9]. Its naturally hollow, tubular form, reinforced with nodes and diaphragms, avoids cracks from spreading and enhances load-bearing performance under both bending and axial stresses. Functionally graded multi-cell structures, inspired by the vascular bundle gradient in bamboo culms, significantly enhance thin-walled design energy absorption [10]. Guided by these insights, [10] developed bamboo-inspired tubes with incorporated bionic elements, illustrating impact resilience superior to that of traditional circular tubes. Extended studies carried out by [11] used simulations to evaluate circulatory-like geometries, demonstrating substantial progress in energy absorption efficiency. To make these designs more implementable for manufacturing, further studies simplified the geometries without compromising their bio-inspired advantages. For example, [12] developed triangular and X-shaped bionic elements that enhanced the performance of previous models, whereas [13] suggested bamboo-inspired multi-cell tubes (BMTs) that mimic ribs and nodes, providing both effectiveness and buildability. Validation through experiments by [14] with the help of advanced fabrication techiques, such as wire electrical discharge machining, subsequently revealed that gradient-thickness and ribbed tubes attained higher energy absorption compared to standard thin-walled designs. These combined results focus on bamboo's role as a model for engineering lightweight, resilient, and crash-resistant systems, highlighting its considerable potential in areas that require both strength and energy efficiency.

- *Horsetail Shape*

The hollow, multi-cell design of horsetail, akin to bamboo, supports its ability to withstand natural forces such as wind and rain [15]. Drawing from these naturally optimized architectures, HBMTs were engineered to improve energy dissipation and crash performance. [16] analyzed six HBMT cross-sectional configurations under lateral compression using nonlinear FEM. The study stated that HBMTs give superior resistance to lateral stress when compared to standard circular and square tubes, emphasising the significance of horsetail-inspired designs in structural engineering.

Evolving the initial concept, [16] implemented foam-filled HBMTs to optimise collision resilience. The inclusion

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of foam substantially enhanced lateral load resistance, energy absorption, and durability, broadening the applicability of HBMTs for applications built to withstand collisions. Nevertheless, while these investigations substantiated considerable advancements under lateral loading, their performance under axial loading remained less understood.

To deal with this gap, [15] carried out an in-depth study on HBMTs exposed to axial dynamic loads. The findings reveal that more cells within the tube cross-section lead to enhanced SEA and initial peak crushing force. This strong correlation illustrated how the multicellular structure of horsetail plants yields significant insights for designing tubular systems resistant to axial impacts effectively.

The aggregated research of [15,16] enhances the significant potential of horsetail-inspired tubes in developing collision-resilient and impact-resistant designs. By refining strategies identified in nature into engineered designs, HBMTs establish themselves as a suitable alternative to conventional tubular systems. The elevated performance of these under both lateral and axial loading forms the basis for future innovations, specifically studies examining experimental validation and the integration of hybrid materials.

- *Cattail*

Cattails, commonly present in aquatic areas such as rivers, lakes, marshes, and streams, demonstrate singular twisting chiral arrangements in their stems and leaves, permitting them to respond optimally to water flow and external stresses [17]. He subsequently determined that cattail leaves possess a multi-cell arrangement, which yields exceptional mechanical strength, specifically in enduring wind loads. Such naturally developed characteristics serve as a key reference for developing engineered structures with improved load-bearing capacity as well as energy absorption efficiency.

Developing further from this model, [18] designed a bionic bumper system that emulated the rib-like internal architecture of cattails. The system combined a bionic cross-beam with a bionic box bumper. Numerical analyses corroborated significant advancements in collision safety, with the bionic crossbeam minimising crush deformation and total weight by 33.33%, and the bionic box gained a 44.44% reduction. These results enhance the efficiency of cattail-inspired geometries in enhancing SEA and overall structural resilience.

- *Material Properties of Bamboo, Horsetail, and Cattail*

The material characteristics of bamboo, horsetail, and cattail vary specifically, illustrating their natural adaptations and functional ecology. Bamboo is distinguished by its impressive mechanical performance, providing maximum tensile strength, structural integrity and adaptability. Such features make it particularly suitable for implementation in construction, furniture, paper development, and craftwork [1]. Its woody, segmented stem supports its structural strength and adaptability, as its capability to disseminate via both seeds and rhizomes enables rapid increase and sustainable harvesting.

Horsetail, by contrast, demonstrates reduced mechanical strength and limited flexibility [1, 2]. Its hollow, jointed stems having whorled branches give less structural efficacy, but it still exhibits a unique biological distinction via spore-based reproduction, setting it apart from flowering plants. Regardless of its mechanical limitations, horsetail has traditionally been recognised for medicinal purposes and plant cultivation applications.

Cattail lies within bamboo and horsetail with respect to its properties. Even though not as strong or durable as bamboo, it outperforms horsetail in both tensile strength and flexibility [2]. Its tall, cylindrical spikes as well as rhizome-driven reproduction allow accelerated development, typically causing improved biomass production compared to horsetail. Aside from its structural properties, cattail exhibits considerable versatility, functioning as a source of edible shoots and rhizomes, as well as a material for weaving, insulation, and conventional handicrafts.Among these three plants, bamboo is recognised as the strongest and most versatile, horsetail is prominent primarily for its exceptional spore-based reproduction and medical application, while cattail's Owing to its accelerated growth and broad functional scope, it is a valuable resource for sustainable uses.

Although substantial progress has been made in creating bio-inspired structures via the implementation of natural geometric patterns to improve strength and efficiency, computational studies remain notably scarce that systematically evaluate their structural longevity and mechanical performance. Existing studies largely focus on conceptual designs as an alternative to statistical assessments, causing uncertainty concerning how geometry and material selection collectively impact structural strength. The quick advancement of AM, especially 3D printing, has allowed for the development of complex geometric forms, yet associated predictive techniques for strength evaluation have not progressed at the same rate. This the absence of comprehensive studies limits the ability to identify optimal combinations of material and geometry for real-world applications. To overcome this disparity, the present study analyse the mechanical performance of bio-inspired structures by determining three distinct materials through three different geometric configurations. The purpose is to obtain reliable computational analyses that can provide a basis for material and design choices in AM. The findings are designed to underpin the development of 3D-printed components with improved reliability, strength, and practical applicability.

III. METHODOLOGY

This investigation follows a biomimetic design strategy, derived from three plant-based systems: bamboo, horsetail, and cattail, each giving unique structural advantages for engineering. Bamboo is noted for its good strength-to-weight ratio and flexibility, resulting from its

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fibre-reinforced cylindrical form. Horsetail, with its segmented stems as well as silica-rich walls, offers resilience and adaptability, while cattail attains reliable load-bearing performance via the arrangement of its vascular tissues even with its lower weight.

To model after these natural designs, accurate 3D models of bioinspired geometries were developed with the help of CATIA, enabling biological microstructures intended for application in mechanical prototypes. A total of 21 plant-based models, standardized at 80 mm diameter and 100 mm height, were prepared—seven representing each plant system—to ensure consistent comparisons. The models underwent explicit dynamic analysis in ANSYS Workbench to investigate their impact strength and transient reaction forces at high strain rates.

By integrating detailed geometric modelling with enhanced numerical simulations, this technique develops a systematic framework for checking impact resistance and mechanical robustness of bioinspired multi-cell tubes. The principal objective is to identify material–geometry pairings that optimise structural efficiency and energy absorption, providing significant knowledge for automotive applications.

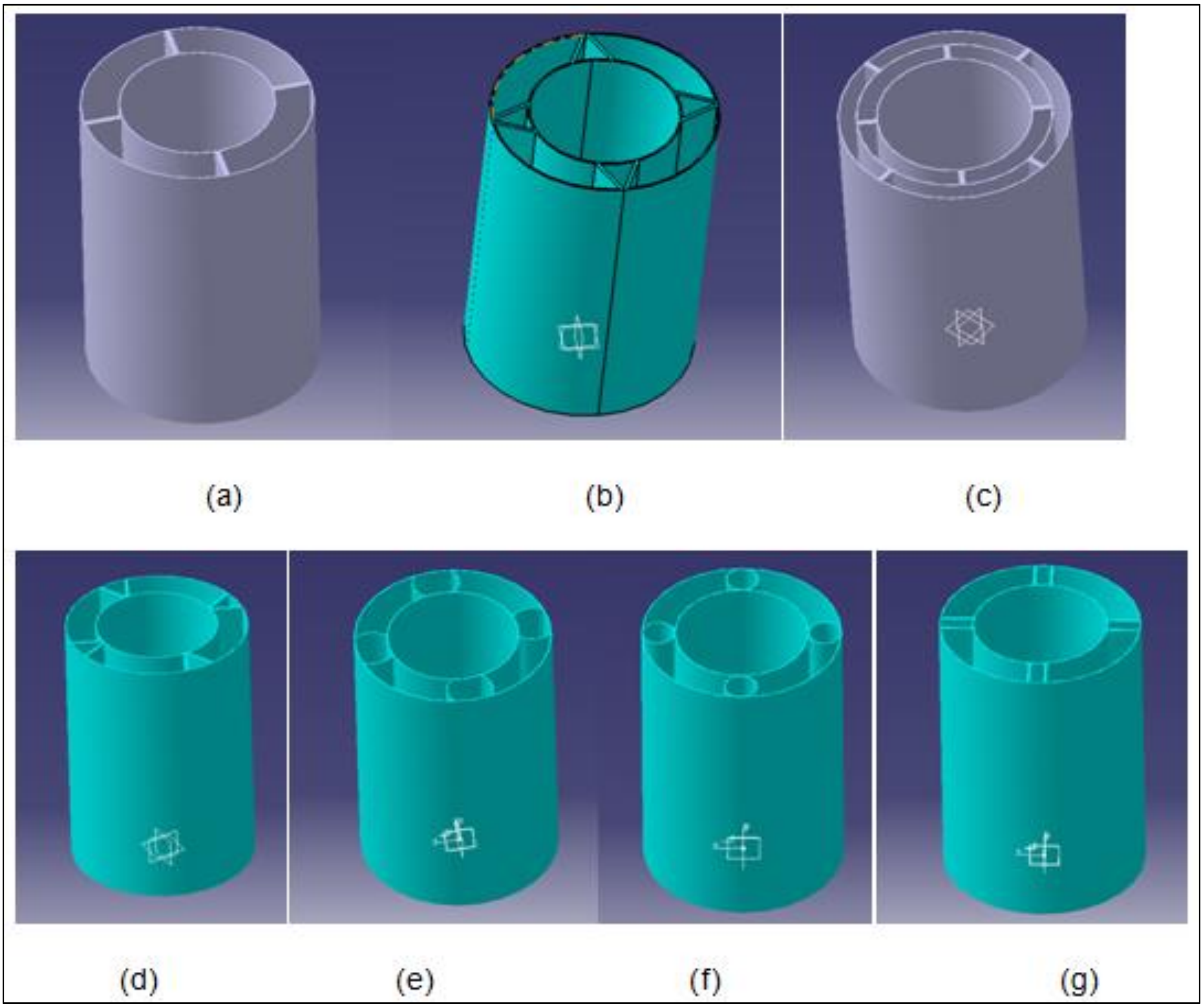

Fig 1 (a) to (g) B01 to B07.

Based on bamboo structures, structural models, designated B01 to B07, have been developed in CATIA, with the prefix “B” referring to bamboo and the numbers acting as unique identifiers. To ensure proper integration through various software tools, the models were exported in both CATIA and STEP file formats. The STEP format, broadly recognised as a widely accepted criterion for CAD data exchange, enables the smooth transfer of such 3D models into ANSYS. Once imported, the geometries could be assessed extensively through advanced simulations to determine their structural integrity, mechanical performance, and total efficiency.

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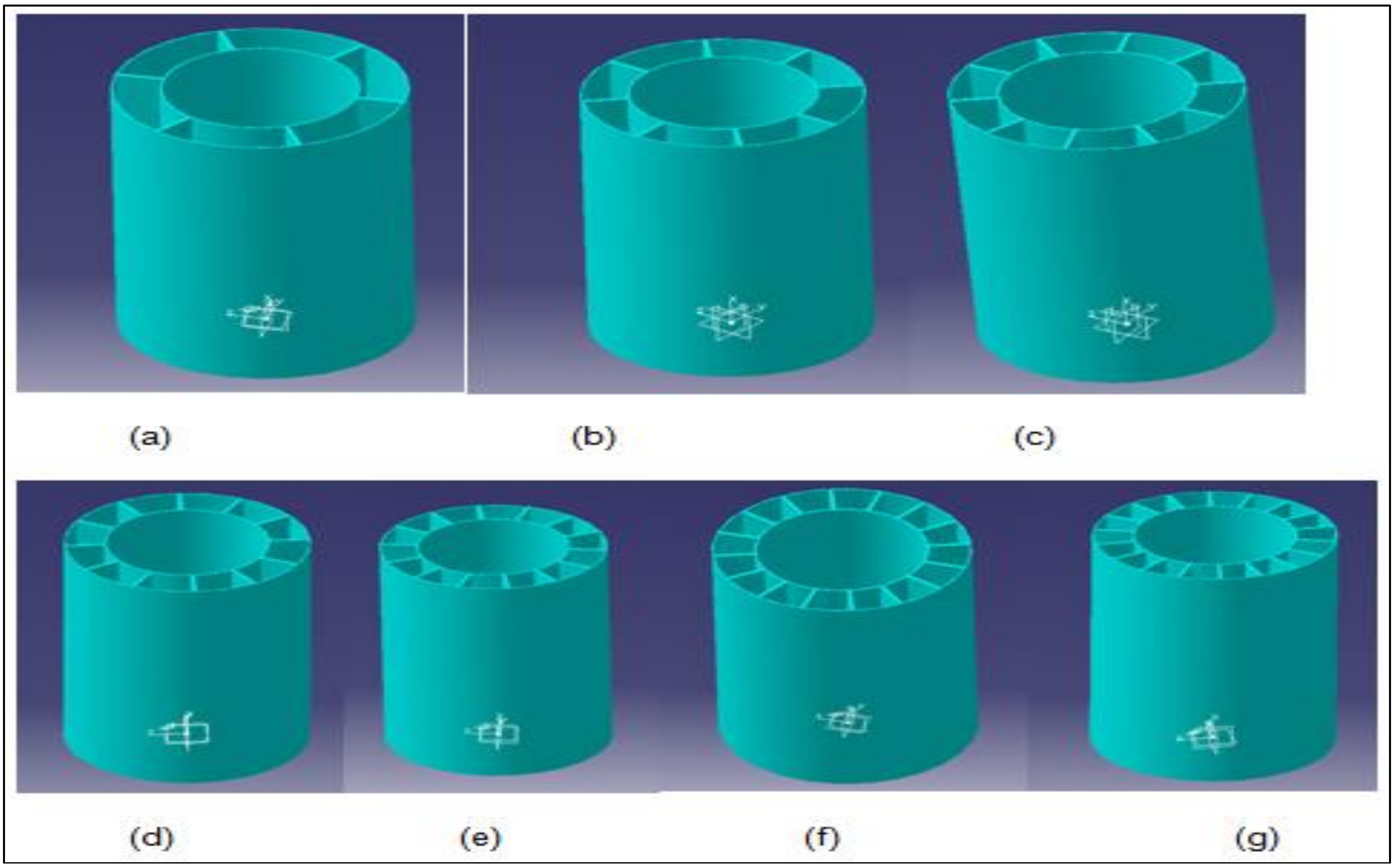

Fig 2 (a) to (g) -H01 to H07.

The above image depict a set of horsetail-inspired structures, developed in CATIA and properly labelled H01 to H07. The prefix "H" classifies the horsetail models, while the numbering promotes clarity and structured presentation. Each structure was built with attention to geometry and detail, employing CATIA's complex modelling features to enable exactness and capability for further analysis and simulation.

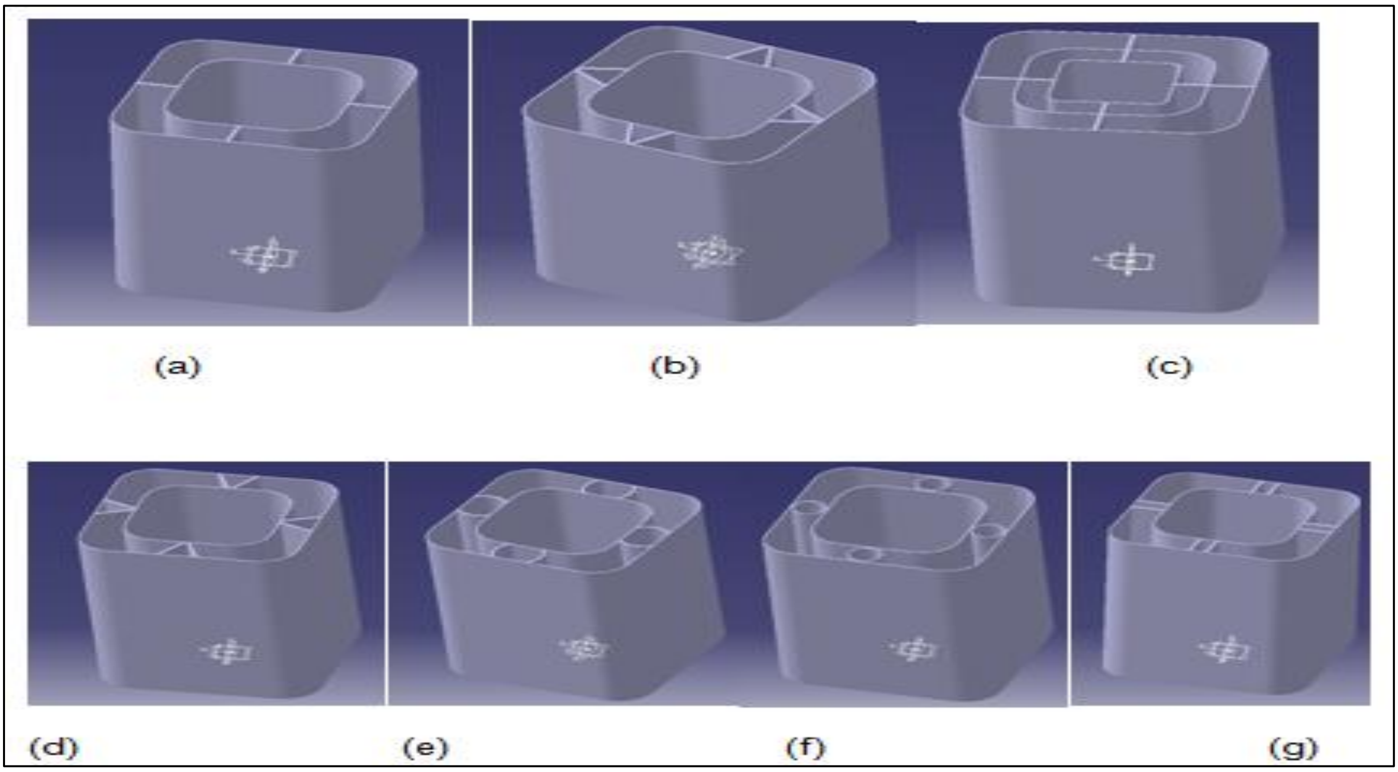

Fig 3 (a) to (g) -C01 to C07.

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The above images show seven cattail-inspired models, modelled C01 to C07. The prefix "C" represents their relationship to cattail, whereas the numbering system gives precision and convenient reference. Each model was meticulously designed to record structural differences while retaining the attribute of cattail form, enabling systematic examination of their influence strength and performance characteristics.

Following the completion of the geometries, the 3D models of the bio-inspired structures have been imported into ANSYS with the help of STEP files to support thorough mechanical analysis, centring on the assessment of compression characteristics. ANSYS, a dynamic FEA platform, allows virtual simulations of how the structures deal with several loading conditions. CATIA-designed fixtures were applied to the top and bottom of each sample during compression tests to maintain alignment, stability, and consistent load distribution.

PLA and ABS, two commonly used and cost-effective 3D printing thermoplastics, were analyzed under high-speed dynamic loading through explicit dynamic analysis to determine structural characteristics. In ANSYS, material properties such as Young's modulus, Poisson's ratio, density, and yield strength were specified, accounting for nonlinear behavior to enhance precision. The simulation design configuration considered the bio-inspired structures as flexible bodies, whereasthe top and bottom supports were characterised by rigidity. Automatic contact generation was applied to effectively represent interactions during deformation.

Meshing was performed with the help of the hexahedral technique, using an optimised element size of 3.5 mm adopted to preserve balance between computational efficiency and solution exactness. For example, model B01 was discretised into 12,034 nodes and 9,563 elements. Boundary conditions have a moving top plate moving at 500 m/s and a fixed bottom surface, simulating a dynamic influence or compression condition over a 1e-4 second interval. Standardisation of boundary conditions and input parameters throughout all models ensured accurate evaluations.

Post-processing tools in ANSYS give valuable outputs, namely total deformation, stress distribution, and reaction forces, offering a detailed understanding of the performance of each bio-inspired design and its potential suitability for practical engineering applications.

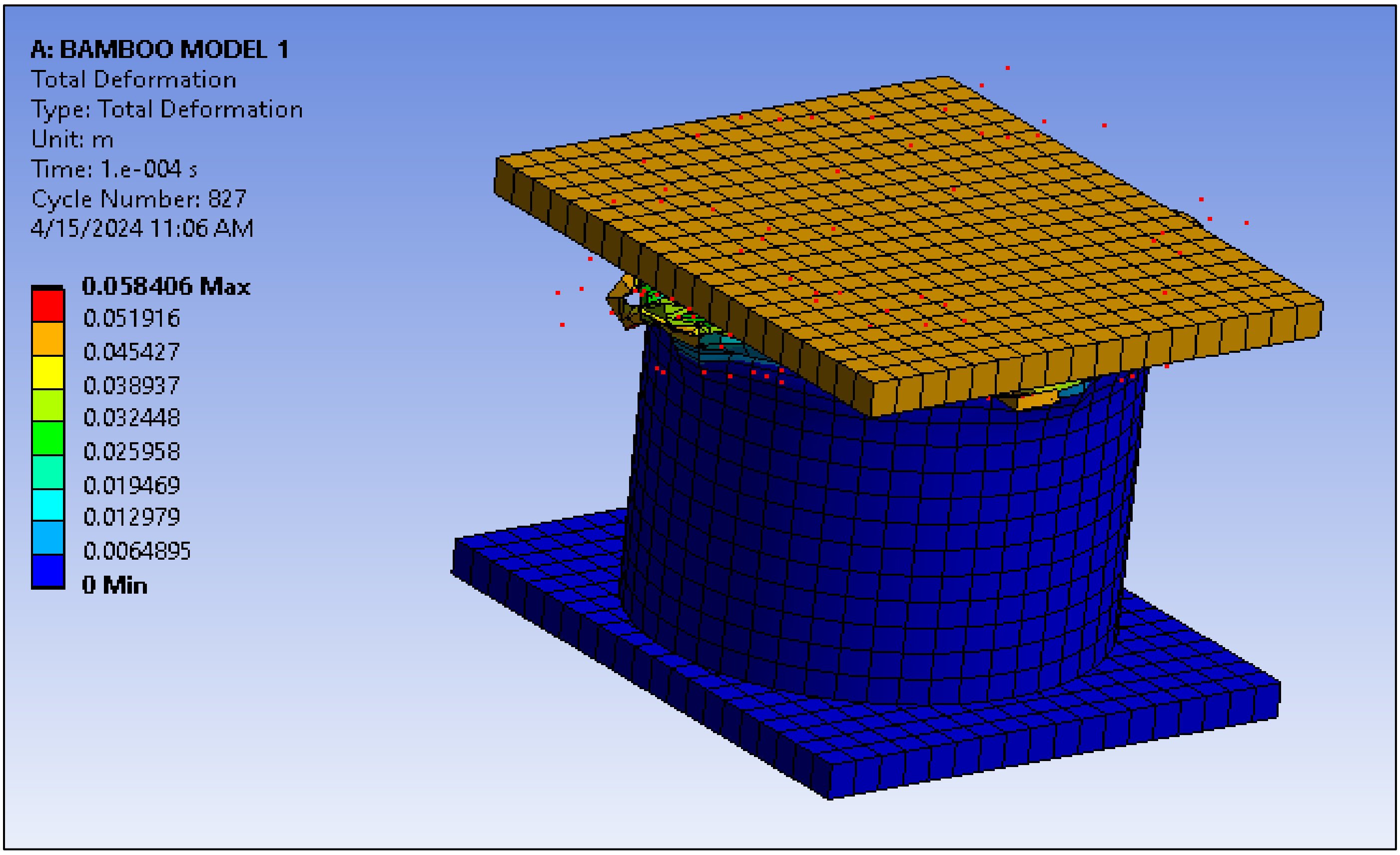

Fig 4 Deformation Plot for Bamboo Model 1.

The deformation behaviour of the B01 model shows constrained displacement near the base, providing that this region experiences minimal impact from the applied load. Conversely, the upper region of the structure goes through noticeable deformation due to the impact load and high velocity, exhibiting evident localised compression. The increased deformation at the top region values 0.0584 m, reflecting the structural response and pointing to probable failure under applied stresses.

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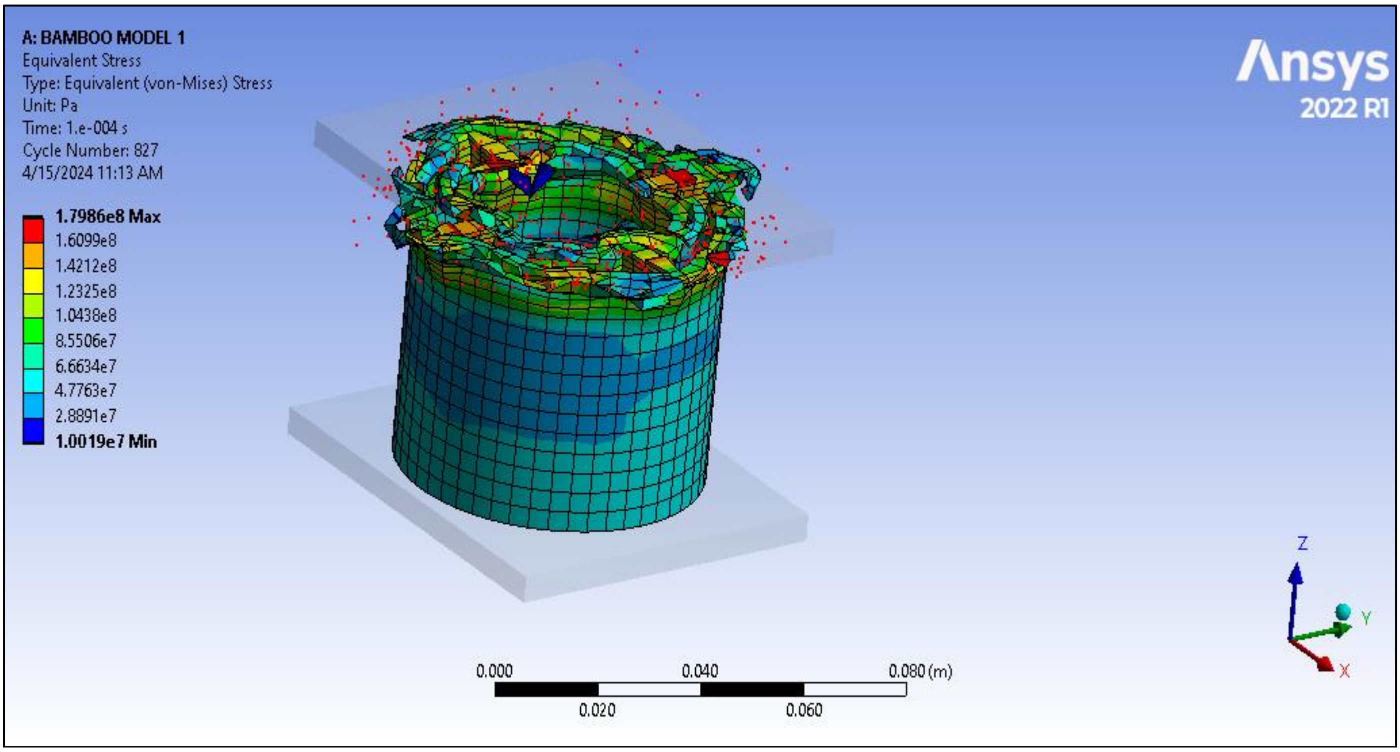

Fig 5 Stress Plot for Bamboo Model 1.

The stress distribution subsequent to impact, the observations reveal the maximum concentration at the top of the structure, revealing substantial damage in that area. At the time interval of 1e-4 seconds, the maximum stress measured is about 1.79 × 10^8 Pa. Under the influence of the applied load from the top support, the structure produces a reaction force demonstrating its resistance to impact. Higher reaction forces are associated with higher structural rigidity, strength, and resistance to deformation or collapse. Assessing reaction loads in conjunction with stress distribution offers a reliable signal of the structure's overall performance and reliability under dynamic loading, emphasising its ability to withstand external forces effectively.

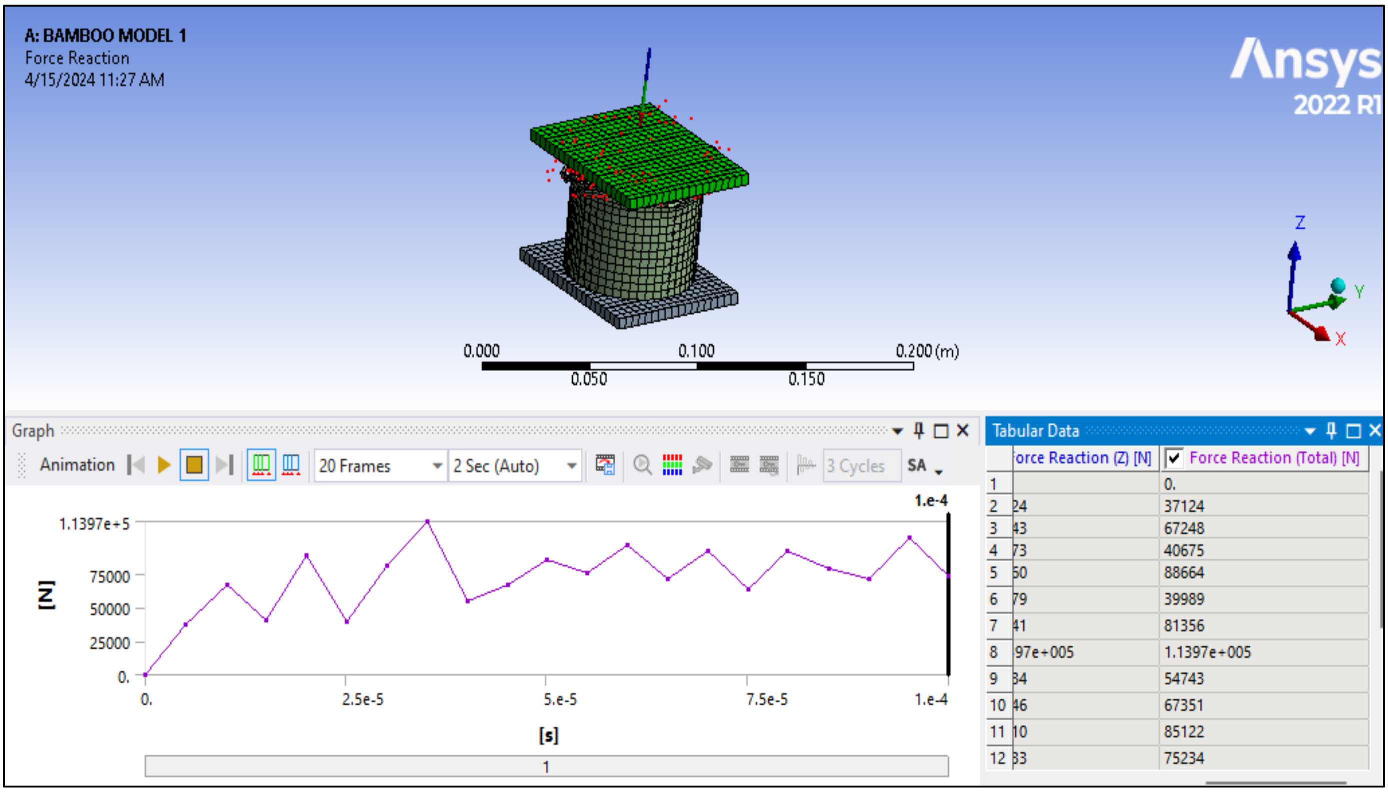

Fig 6 Reaction Load on Biostructure.

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When the applied stress improves, the reaction load usually begins at zero and then gradually increases with time, indicating irregular variations throughout the procedure. Such differences are caused by the "jerking effect" correlated with impact loading, where abrupt and irregular variations in the applied force generate associated instabilities in the reaction load. Despite such irregularities, determining the overall pattern and magnitude of the reaction load provides valuable information into how the structure behaves under dynamic impact conditions. In this analysis, the highest reaction load is measured to be 1.13 × 10^5 N, determining the peak resistance the structure must endure during loading.

IV. RESULTS AND DISCUSSION

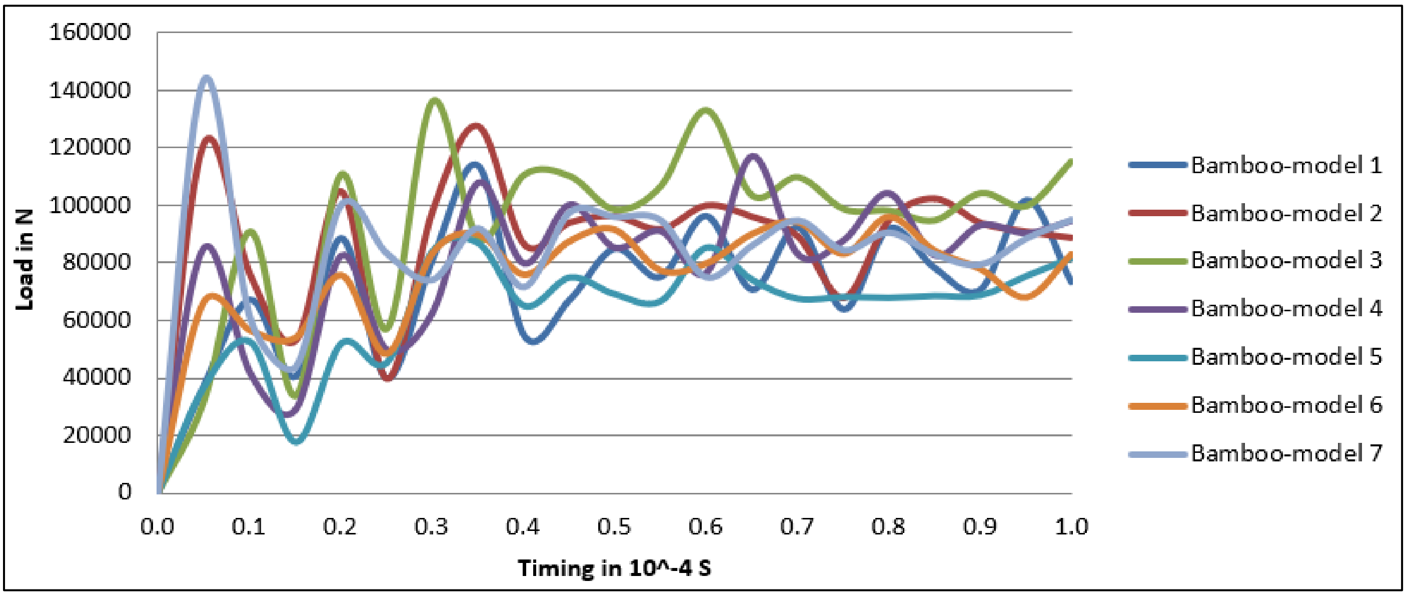

Fig 7 ABS Material Reaction Load.

The fig shown above is the reaction force with respect to time provides information into the performance of the bamboo-inspired models. From this set, model 7 depicts a powerful initial reaction force and regulates a relatively stable response via loading, reflecting solid resistance to applied forces. In contrast, model 5 registers the minimal reaction force, indicating substandard structural capacity. The model 3 is notable for its remarkable rigidity, retaining the highest reaction force of all models and withstanding up to 140 kN before any signs of damage appear. This consistent performance underscores model 3 superior structural durability and resistance to deformation. In general, analysing reaction forces results in identifying designs with higher stiffness and durability, enabling strategic choices in the selection of material and geometry optimisation to develop reliable biomimetic structures for real-time applications.

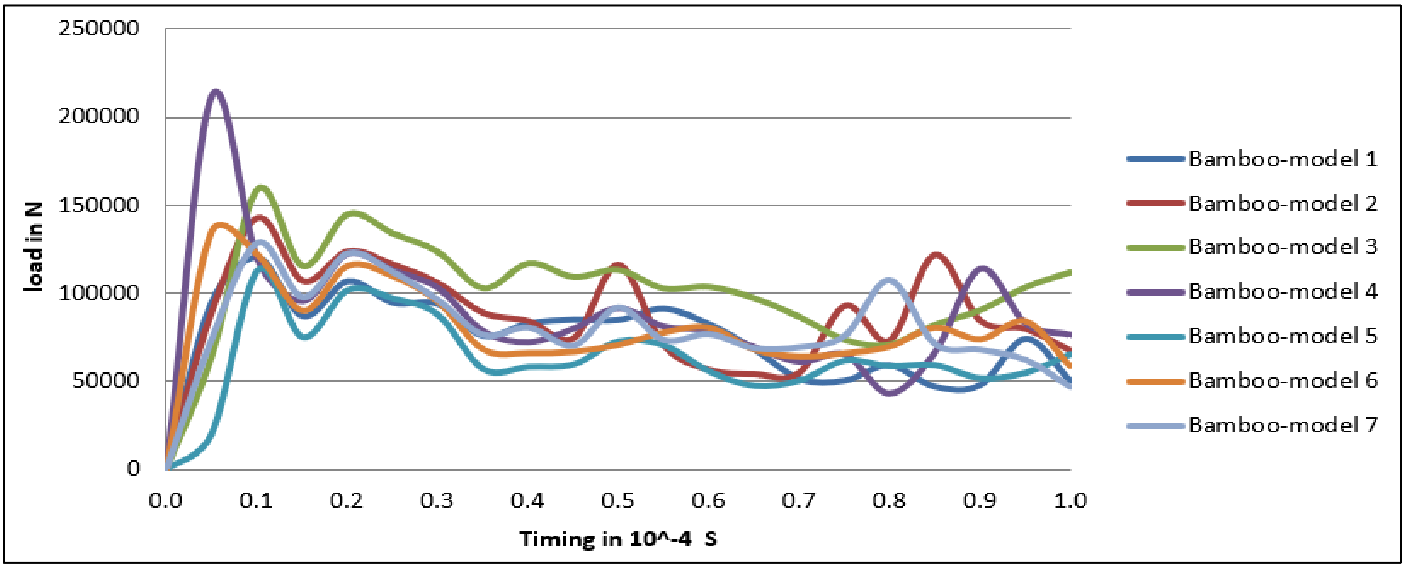

Fig 8 PLA Material Reaction Load.

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The fig shown above is the reaction force for bamboo structures fabricated using PLA demonstrates that model model 3 offers the maximum and optimal consistency all through loading, able to endure up to 150 kN before any damage becomes evident. This represents maximum strength and resistance to deformation. Model 4 depicts a significant primary force that reduces gradually, while model 5 saves the least overall response. While comparing materials, PLA demonstrates itself as 6% higher than ABS in regard to the model 3 model, proving it to be the most suitable alternative for subsequent simulations consisting of horsetail- and cattail-inspired structures.

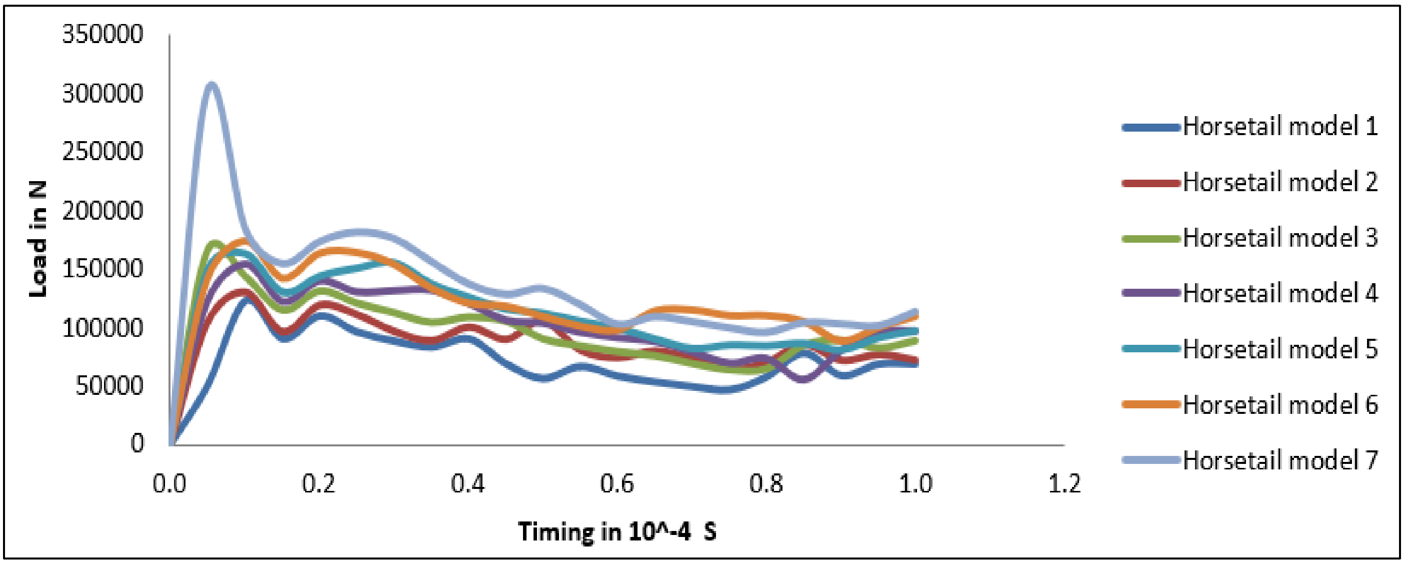

Fig 9 Horsetail Structure Reaction Load.

Evaluation of mechanical performance in horsetail-inspired structures denotes that model model 7 exhibits the best, enduring a reaction load of 300 kN before collapse, whereas model 1 yields the lowest load response, demonstrating lower stiffness. This difference can be attributed to the number of internal stiffeners: model 7 integrates 18, whereas model 1 has only 6, resulting in a 60% improvement in strength. This analysis demonstrates the fundamental role of internal stiffeners in improving the durability and load-bearing ability of horsetail-based structural designs.

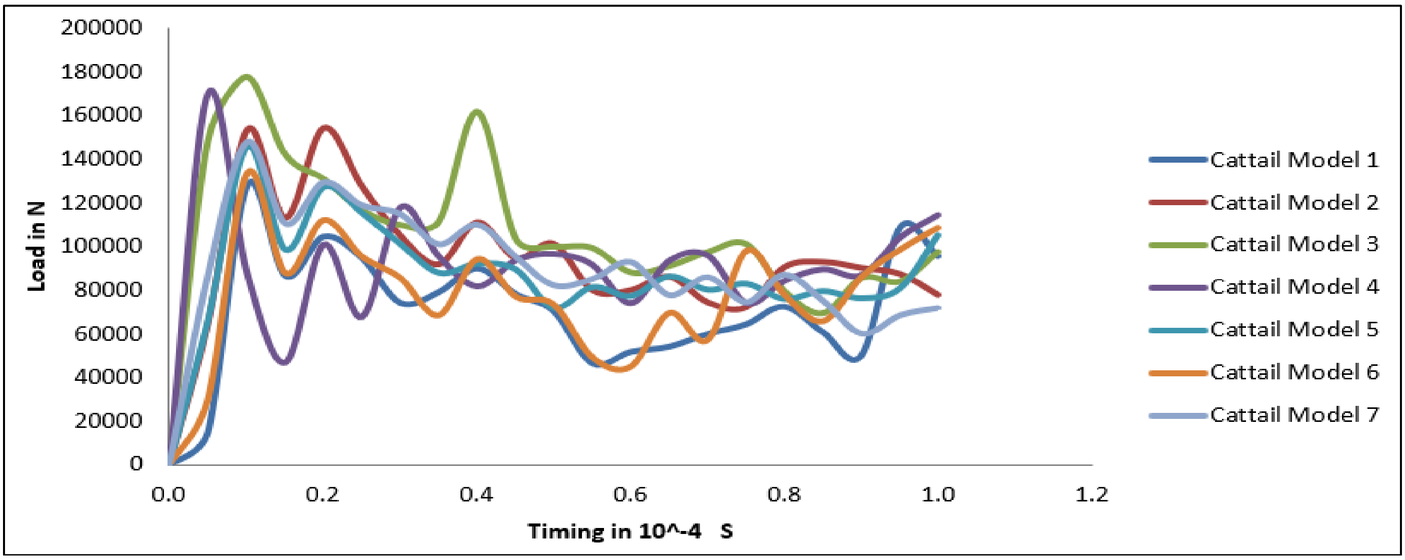

Fig 10 Cattail Structure Reaction Load.

Considering the 7- cattail-inspired models, C-03 indicates the highest strength, collapsing at a reaction load of approximately 180 kN, whereas C-05 was the weakest, collapsing at 130 kN. Compared to all plant-based structures, the bamboo B-03 model represented exceptional stiffness and ability to withstand deformation, critical for structural integrity in real-world uses. Likewise, the horsetail H-07 model represented extraordinary rigidity, capably enduring external forces. The cattail C-03 model also represented remarkable stiffness, indicating it is well-suited to dynamic loading conditions. Depending on this stiffness evaluation, the robust and reliable models from every plant-inspired design were opted for 3D printing applications.

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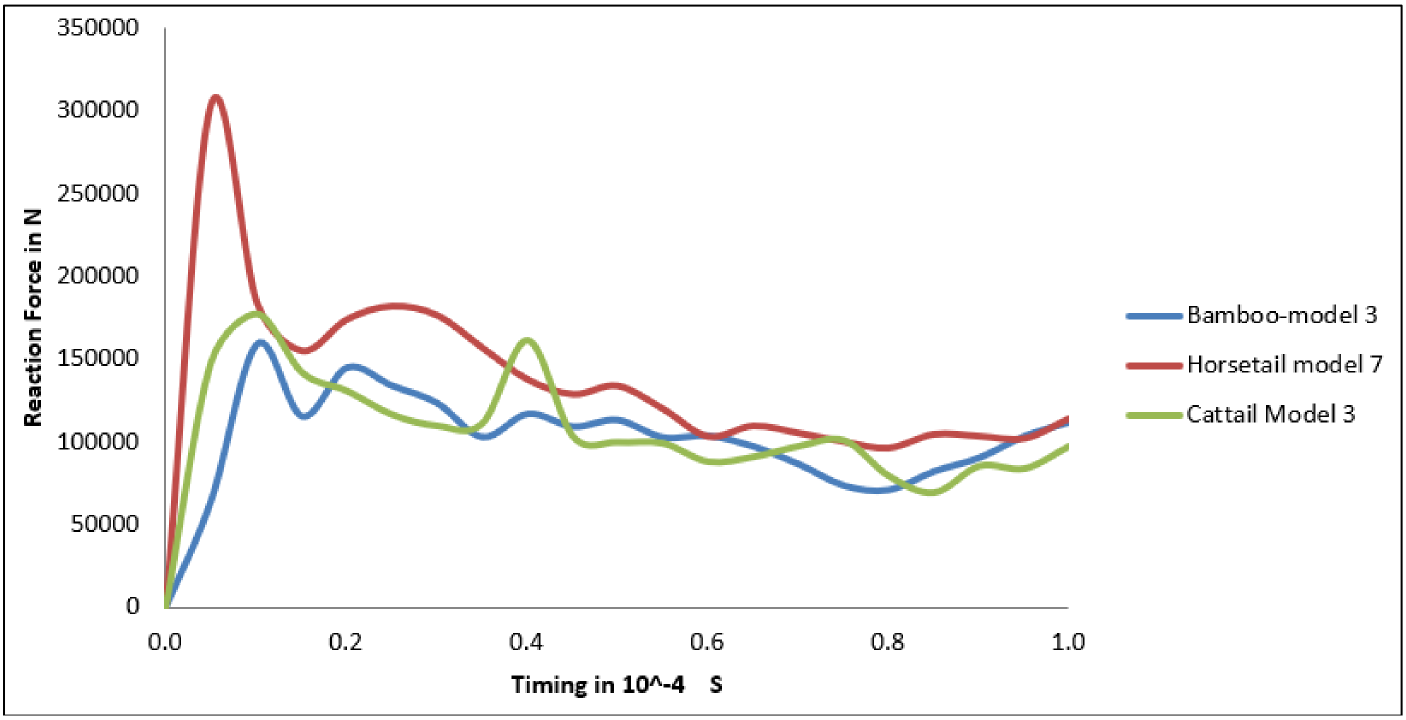

Fig 11 Optimum Structures Reaction Load.

The stiffness comparison graphical representation denotes that the horsetail-inspired structure represents higher rigidity than both bamboo- and cattail-based designs, focusing on its higher resistance to deformation and superior ability to sustain structural integrity under loading. Despite the fact that bamboo and cattail models also depict high stiffness, their total performance is comparatively less. The horsetail structure specially demonstrates 43.3% higher strength compared to the bamboo and cattail models, emphasizing its robust mechanical resilience. Simulation These observations affirm that horsetail-based designs, particularly model H-07, clearly outperform competing designs in both strength and durability. Due to this reason, H-07 offers the most reliable solution for applications requiring excellent performance, making it the suggested design for 3D printing because of its proven strength and higher reliability.

V. CONCLUSION

Numerical analyses were performed to evaluate the strength and performance of bioinspired structures. Among these bamboo models, B-05 measured the minimum reaction force, demonstrating lower strength, whereas B-03 represented excellent durability by sustaining the highest reaction force and bearing loads of 140–150 kN prior to failure. Among these materials, PLA exhibited consistently higher performance than ABS, demonstrating its role as the highly reliable choice for further analysis. For the horsetail-inspired structures, model H-07 attained the maximum reaction load and superior strength, highly resulting from its eighteen internal stiffeners that showed critical for sustaining structural integrity. Within the cattail-inspired set, model C-03 exhibited maximum load-bearing capacity, causing it opt for conditions consisting dynamic influence.

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