Abstract

Since time immemorial, materials Science and engineering have played a significant role in nearly all developmental endeavors. Historical periods of human activity are designated based on the advancement and utilization of materials, such as the Stone Age, the Iron Age, and the contemporary Silicon Age. Materials have facilitated the development of several technologies, encompassing transportation, agriculture, housing, food science, environmental science, medicine and health, information and communication, as well as structural materials such as textiles. The objective is to enhance the development and application of these materials with requisite qualities while ensuring their affordability to meet human demands. The excitement for materials science and engineering has been enormously enhanced by its tight ties to other fields and its influence on everyday life. Auxetic refers to a class of exceptional materials that increase in thickness when subjected to tensile forces applied perpendicularly. Auxetic materials are substances or structures that exhibit zero or negative Poisson's ratio. Poisson's ratio refers to the phenomenon where, when a material is elongated in the longitudinal direction, it expands in the transverse direction, in contrast to typical materials that compress transversely under comparable conditions. Poisson's ratio is defined as the negative ratio of lateral or transverse strain to longitudinal strain, $\upsilon = (-\varepsilon trans)/\varepsilon load$. Poisson's Ratio is a dimensionless quantity. Auxeticity manifests across various levels and types of materials, including metals, polymers, plastics, ceramics, and fibrous substances. Concentrating on fibrous materials, as they provide a promising category for composite synthesis across many applications. Fibrous materials manifest in multiple forms, including fibers, yarns, textiles, and their corresponding composites. Fibers constitute the primary components of other fibrous formations. These exist in three forms: natural, synthetic, and regenerated.

Research has been conducted on the production of 2D and 3D fabrics. 3D fabrics possess considerable thickness, unlike 2D fabrics. 3D fabrics possess numerous advantages over traditional 2D fabrics and typically constructed 3D constructions, such as stitched 3D fabrics that consist of multiple stitched 2D fabric layers to attain considerable thickness. In the case of 3D fabrics, integrated structures can be constructed, hence decreasing the delamination failure mode.

Auxeticity can be obtained at various levels; hence, it can be achieved in textiles. Researchers have found multiple methods and technologies for the fabrication of auxetic textiles. Auxetic textiles exist as fiber, yarn, fabric, and composites. Advancements in textile and fiber engineering enable the production of auxetic materials using many textile manufacturing methods, including weaving, knitting, and nonwoven techniques, which can subsequently be converted into composite materials for enhanced fiber reinforcement. Textile materials have significant structural variety, material flexibility, and lightweight properties, rendering them an intriguing possibility for the production of various auxetic materials and structures. Investigations have been conducted to develop diverse varieties of auxetic fabrics utilizing multiple ways, i.e., non-woven, knitted, braided, and woven technologies. Non-woven auxetic fabrics are produced by laser cutting or thermo-mechanical techniques. The laser cutting approach employs lasers to cut auxetic geometric patterns, while the thermo-mechanical procedure transforms standard non-woven materials into auxetic non-woven by means of heating and triaxial compression. Auxetic knitted fabrics represent the most extensively studied domain within auxetic textiles, as diverse auxetic geometries have been achieved through the meticulous arrangement of the face and back loops.

Auxetic knitted materials may be used in diverse medical textiles, compression bands, and similar areas. Braided auxetic fabrics are developed on the same principle as auxetic yarn. The braided fabric serves as the main structure, with a rigid yarn encircling it.

In comparison to other textile fabrics, woven structures provide a diverse array of structural and mechanical properties, rendering them an appropriate material for composite reinforcement. Auxetic woven fabrics have been created based on two principles: firstly, auxetic yarn is used as the weft, which confers auxetic properties to the fabric, rendering it auxetic. Secondly, auxetic geometry can be implemented through the amalgamation of standard yarns with varying moduli and weave patterns combined with diverse float lengths. Three-dimensional woven auxetic structures can be fabricated utilizing several matrix systems, such as green epoxy, polyurethane foam, silicone rubber gel, and unsaturated polyester. Auxetic materials have diverse qualities, including shear resistance, indentation resistance, impact resistance, and blast resistance. These can be used as energy-absorbing materials. These additionally provide acoustic insulation and vibration attenuation. Due to their auxetic structure, they provide variable permeability, meaning the pore size can change according to the applied force level. They also exhibit synclastic behavior. Consequently, due to these features, auxetic materials possess a diverse array of applications. These materials can be utilized in the aviation sector due to their superior shear resistance and synclastic properties. Auxetic materials have also been utilized in the maritime sector to construct ships' hulls because of their superior impact resistance. Auxetics has been utilized in medical textiles for applications such as stents, prostheses, wound treatment, and bone replacements. Auxetics can be utilized in sports protective apparel, such as knee pads, due to their superior impact resistance.

They have been utilized for maternity and children's apparel as well. Despite the benefits of enhanced mechanical qualities previously mentioned, auxetic materials exhibit diminished stiffness and strength owing to their geometric arrangement, namely their porous structure. Certain constraints hinder the design and production of auxetic materials due to their requirement for significant porosity. Consequently, auxetic materials may be unsuitable for load-bearing applications. Typically, auxetic structures are fabricated using additive manufacturing processes, which are expensive. The intricacy of auxetic geometry results in increased production expenses. Auxetic textiles face difficulties in cost and mass manufacturing for fiber and yarn-based fabrics; knitted auxetic fabrics exhibit stability issues due to their loop structure. Given their structural stability, wearability, and cost-effective continuous manufacturing advantages, woven auxetic textile structures seem poised to meet numerous demanding applications in the near future.

Investigations have been conducted to create auxetic woven textiles utilizing re-entrant hexagonal, foldable, and rotating rectangular geometries. Numerous auxetic geometries remain to be actualized in the fabric. This project aims to build novel hybrid auxetic geometries and incorporate these unattempted designs into woven fabrics. The engineering design of the newly designed hybrid auxetic geometry is also emphasized. To date, 3D woven auxetic structures have not been manufactured on any weaving machine, resulting in a non-continuous manufacturing approach. However, we have successfully generated 3D woven auxetic structures using a typical dobby shedding system. The translation of auxetic geometry into 3D woven constructions has not been pursued through manual or CAD-based design methodologies. This project investigates the design of auxetic 3D woven fabrics using a CAD system.

The exploration of auxetic composites has been limited among researchers. Consequently, an effort has been undertaken to identify a suitable matrix system that is consistent with the auxetic reinforcement to demonstrate auxeticity in its composite form. The mechanical performance of the designed fabric and composite structures is evaluated for their tensile, shear, puncture, and impact properties. This research concentrates on the design engineering, modeling, development, and characterization of 2D and 3D woven auxetic fabrics and their composites.The results underscore the adaptability of weaving as a scalable method for creating auxetic structures with remarkable mechanical properties, hence expanding opportunities in technical fabrics, protective materials, and sophisticated engineering applications. This research significantly contributes to the creation of auxetic fabrics through various geometries. The work effectively attained auxetic behavior in diverse fabric configurations, such as foldable stripes, re-entrant hexagons, and wave patterns, by integrating differential shrinkage and meticulously constructing loose and tight weave patterns. These structures achieved NPR values as low as -0.5, illustrating the pivotal influence of geometry in customizing auxetic characteristics. The study creates a solid framework for developing auxetic textiles with adjustable mechanical properties, rendering them suitable for use in technical textiles, fashion, and engineering industries.

The study incorporates analytical modeling and hybrid geometries to enhance the theoretical framework of auxetic fabric design. Analytical tools based on Python were utilized to simulate hybrid auxetic structures, which were further validated by experimental techniques. Discrepancies between theoretical predictions and experimental outcomes were noted due to inter-fiber interactions, yet the findings enhance the refinement of computer models for future research.

Among hybrid designs, fabrics featuring elliptical core structures (2DEF05) demonstrated enhanced tensile and impact performance, underscoring the importance of material distribution and geometric inventiveness in optimizing mechanical qualities.

A notable progression in this research is the creation of 3D woven auxetic fabrics, which demonstrate enhanced mechanical capabilities attributable to their three-dimensional architecture and material choice. By integrating high-performance fibers like Kevlar and core-spun polyester with a spandex core, these materials exhibited improved tensile strength, shear resistance, and puncture resistance. Uni-stretch 3D fabrics surpassed their bi-stretch equivalents, mainly owing to Kevlar's superior modulus and the implications of differential shrinkage in areas with a looser weave. Low-velocity impact testing further confirmed the enhanced energy absorption capability of these textiles, especially those featuring foldable and double-arrow designs. These findings identify 3D woven auxetic fabrics as viable options for high-performance applications, such as protective textiles, aerospace materials, and impact-resistant structures.

The study examines the influence of weave design on auxetic behavior, uncovering essential insights into the correlation between structural characteristics and mechanical performance. In both 2D and 3D textiles, augmenting the float length improved auxeticity by facilitating differential shrinkage. Excessively long floats affect structural integrity, highlighting the necessity for an ideal equilibrium. The research indicates that fabrics with enhanced weave specifications have higher mechanical characteristics, such as increased tensile strength, shear resistance, and impact durability. These findings offer a systematic methodology for the design of auxetic textiles customized to certain application needs.

This work significantly contributes by integrating auxetic reinforcements into several matrix systems to create auxetic composites. The research emphasizes the impact of matrix composition, including epoxy resin, flexible epoxy resin, and silicone rubber gel, on the mechanical characteristics of the composites. Silicone rubber gel enabled optimal auxeticity and energy absorption, while epoxy matrices offered enhanced tensile strength and shear resistance. These findings underscore the adaptability of auxetic composites in fulfilling various performance demands, from impact absorption to structural reinforcement. The research definitively shows that auxetic composites surpass non-auxetic composites in key aspects, including impact energy absorption, tensile strength, and shear resistance. This research provides a robust basis for forthcoming advancements in auxetic fabrics and composites. This work facilitates the large-scale application of auxetic materials in many industrial sectors by the integration of theoretical modeling, experimental validation, and materials engineering. The results enhance scientific understanding and provide practical insights for the advancement of auxetic textiles in protective, technical, and consumer applications.