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Optimization and Analysis of Composite Fiber Reinforced Aero-Structures

Dr. MANTHRI HANUMAN, C SHIVA KUMAR

Associate Professor, St Mary's Group of Institutions, Hyderabad, India

Asst. Professor, St Mary's Group of institutions, Hyderabad, India

ABSTRACT: This study focuses on the analysis and optimization of composite structures for lightweight design specifically for roofs, using carbon fiber reinforced polymers (CFRP). The aim is to enhance the lightweight characteristics of automotive roofs, reduce material costs, and improve manufacturing performance through a systematic design and optimization approach. By combining free size optimization and size optimization methods, a design method is proposed to establish a link between conceptual and detailed design stages, resulting in an optimized CFRP roof. The article begins by elucidating the fundamental principles of composite mechanics, including the stress-strain theory of single-layer plates and the stiffness and strength theory of laminated plates. Composite structures offer unmatched design potential as the laminate material properties can be tailored almost continuously throughout the structure. However, this increased design freedom also brings new challenges for the design process and software. In recent years the study has developed a comprehensive framework for composite optimization, leading the design from concept to ply-book details. Usage of fiber reinforced composite material entered a new era when leading aircraft OEMs took an unprecedented step to design and manufacture essentially full composite airframe for commercial airliners. This software package has seen increasing adoption among aerospace OEMs, as demonstrated in the Bombardier application process described in this study.

KEYWORDS: carbon fiber reinforced polymers (CFRP), Aero-Structures, analysis and optimization, composite mechanics, stress-strain theory, Composite structures.

I. INTRODUCTION

Composite materials offer great potential for lightweight design in mechanical engineering applications. This research study focuses on the analysis and optimization of composite structures with the aim of achieving enhanced lightweight characteristics while maintaining structural integrity. The study begins with an overview of the importance of lightweight design in various industries and the benefits of using composite materials. It then delves into the analysis techniques employed to evaluate the mechanical properties of composite structures, including finite element analysis, experimental testing, and computational modeling. The optimization aspect of the research study focuses on exploring different approaches such as topology optimization, material selection, and structural design optimization. These method-logies aim to maximize the structural performance while minimizing weight and maintaining design constraints. Additionally, advanced manufacturing techniques specific to composite materials, such as automated fiber placement and resin infusion, are discussed in relation to their impact on the optimization process. Lightweight fiber-reinforced polymer (FRP) composite has been widely used in aerospace industry due to its high strength-weight ratio, high temperature resistance, outstanding design ability to meet different requirements and the ability to integrate large-scale integral structures. The application of FRP not only enhances their safety and energy-efficient significantly, but also is environment-friendly. Because of the benefits, the usage of FRP composite in aerospace industry will increase continuously. Design of FRP composite include the material selection, the determination of material content, the internal structure of composites and so on, which pursuits to figure out the relationship between their mechanical properties and these parameters. Manufacturing process of composites is complicated and primarily determines whether the final performance of the composites can reach the designed value.

II. LITERATURE REVIEW

Grace Njeri Wamuti (2023) High-density poly-ethylene (HDPE) is a nonbiodegradable recyclable plastic which is widely utilized in single use packaging applications. Consequently, it constitutes a significant amount of plastic waste

found in landfills. From literature, it has been shown that parts produced using composites of HDPE with carbohydrate-based polymers, such as thermoplastic starch (TPS), experience mechanical degradation through hydrolytic degradation process. The possible utilization of recycled-HDPE (rHDPE) and TPS composite in non-conventional manufacturing processes such as Fused filament fabrication (FFF) has however not been explored. This study explores the potential application of rHDPE and TPS composites in FFF and optimizes the extrusion process parameters used in rHDPE-TPS filament production process. Taguchi method was utilized to analyze the extrusion process. The extrusion process parameters studied were the spooling speed, extrusion speed and the extrusion temperatures.

Congge Wen (2021) Based on the cohesive zone model, the 2D mesostructures were developed for numerical studies of multi-phase hooked-end steel fiber reinforced concrete under uniaxial compression. The zero-thickness cohesive interface elements were inserted within the mortar, on interfaces of mortar and aggregates and interfaces of mortar and fibers to simulate the failure process of fiber reinforced concrete. The results showed that the numerical results matched well the experimental results in both failure modes and stress-strain behavior. Hooked-end steel fiber reinforced concrete exhibited ductile failure and maintained integrity during a whole failure process. Compared with normal concrete, HES fiber reinforced concrete was greater stiffness and compressive strength; the descending branch of the stress-strain curve was significantly flatter; the residual stress was higher.

José Luis Ramírez Ascheri (2021) X-ray diffractograms, optic and electronic microscopy were used to study the structural changes on extruded orange pulp using a Brabender® laboratory single-screw extruder (GNF 1014/2, 20:1, L/D). The results showed that most of the cellulose would be in the amorphous state, with small crystalline areas in the angular region of $2\theta = 14.5^\circ$. The evaluated extrusion conditions did not affect the crystallinity of the raw cellulose, maintaining the size of the crystalline regions in the angular region of $2\theta = 22.5^\circ$. Neutral detergent solubilized the crystalline areas of potassium citrate and cellulose, formed during the extrusion process. However, these conditions did not affect the crystallinity of the raw cellulose. In addition, no change was observed in the crystallinity of pectin. The electron microphotographs allowed for the estimation of the heterogeneity of orange pulp and assessment of the difference of resistance between the walls of the buds and juice vesicles.

M. Mehedi Hasan (2020) This study work involves bunch experiments to investigate the effect of contact time, pH, and adsorbent dose on the extent of adsorption by bio-composites. Adsorption capacity of Chromium (VI) onto chitosan coated with banana and areca fiber was investigated in a batch system by considering the effects of various parameters like contact time, initial concentration, pH and adsorbent dose. The chitosan and fibers (banana and areca) were then cross-linked with glutaraldehyde to remove chromium [Cr (VI)] from water via static adsorption. The standard deviation results of pH, time and amount of treated banana fiber test results were 1.831, 2.693 and 5.469 ppm congruently. On the other hand, the standard deviation results of pH, time and amount of treated areca fiber test results were 3.293, 2.673 and 4.152 ppm individually. Fourier transform infrared (FT-IR) spectroscopy analysis indicated that both amino and hydroxyl groups of chitosan, banana and areca fiber were engaged in the adsorption.

T. Krishna Rao (2019) In this study, boron fiber powder and graphite is reinforced to Al 2024 alloy to develop hybrid metal matrix composite by stir casting process. Hybrid MMCs developed with different weight fraction for 4%, 6%, 8% and 10% of boron fiber and 2% of graphite. Stirring parameters are optimized to obtain solid casting. Reinforcements are poured into molten aluminium at 15 g/min and stirrer is rotated for 5 minutes at 250 rpm with two stages stirring. 1% of magnesium was added to improve the wettability of Al 2024. Cast samples are machined as per the standards to investigate the microstructure, physical and mechanical properties. Optical and SEM analysis was carried out on machined sample to study the uniform distribution of particles. XRD and EDAX analysis is carried out to confirm the dispersion of particles into the matrix. Uniform distribution of the particles is found in optical and SEM images for these stirring parameters.

Fiber-reinforced composite

A fiber-reinforced composite (FRC) is a composite building material that consists of three components:

- the fibers as the discontinuous or dispersed phase,
- the matrix as the continuous phase, and
- the fine inter phase region, also known as the interface.

This is a type of advanced composite group, which makes use of rice husk, rice hull, rice shell, and plastic as ingredients. This technology involves a method of refining, blending, and compounding natural fibers from cellulosic

waste streams to form a high-strength fiber composite material in a polymer matrix. The designated waste or base raw materials used in this instance are those of waste thermoplastics and various categories of cellulosic waste including rice husk and saw dust.

Fiber Reinforcements

The major component of composite materials is the fiber reinforcement. The fiber reinforcement provides strength and stiffness in the direction that the fibers are aligned. The three most common fiber types found in aerospace applications are carbon fiber, glass fiber, and aramid fiber. These fiber types have different chemical compositions at the molecular level that generate different physical and mechanical properties at the macroscopic fiber level. Important properties of fibers include their strength, stiffness, toughness, temperature capability, density, conductivity, chemical compatibility, fatigue life, and cost.

Continuous fiber-reinforced materials

Fiber-reinforced composites are a combination of materials, in which a matrix made of plastic, ceramic, or metal is reinforced with different materials in the form of fibers or fiber-based textiles. A property profile is achieved by the combination of the respective properties, which is different from the property profile of the individual components. The basic principle of fiber-reinforced composites the reinforcing fibers carry the bulk of the load. Shaping, load distribution, and transmission as well as the protection of the fibers are tasks of the embedding matrix.

Fibre-reinforced plastic

Fibre-reinforced plastic (FRP; also called fibre-reinforced polymer, or in American English fiber) is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually glass (in fibreglass), carbon (in carbon-fibre-reinforced polymer), aramid, or basalt. Rarely, other fibres such as paper, wood, boron, or asbestos have been used. The polymer is usually an epoxy, vinyl ester, or polyester thermosetting plastic, though phenol formaldehyde resins are still in use. FRPs are commonly used in the aerospace, automotive, marine, and construction industries. They are commonly found in ballistic armour and cylinders for self-contained breathing apparatuses.

Industrial composites

The industrial composites industry has been in place for over 40 years in the U.S. This large industry utilizes various resin systems including polyester, epoxy, and other specialty resins. These materials, along with a catalyst or curing agent and some type of fiber reinforcement (typically glass fibers) are used in the production of a wide spectrum of industrial components and consumer goods: boats, piping, auto bodies, and a variety of other parts and components.

Advanced composite materials

In materials science, advanced composite materials (ACMs) are materials that are generally characterized by unusually high strength fibres with unusually high stiffness, or modulus of elasticity characteristics, compared to other materials, while bound together by weaker matrices. These are termed "advanced composite materials" in comparison to the composite materials commonly in use such as reinforced concrete, or even concrete it. The high strength fibers are also low density while occupying a large fraction of the volume Advanced composites exhibit desirable physical and chemical properties that include light weight coupled with high stiffness (elasticity), and strength along the direction of the reinforcing fiber, dimensional stability, temperature and chemical resistance, flex performance, and relatively easy processing. Advanced composites are replacing metal components in many uses, particularly in the aerospace industry.

III. RESEARCH METHODOLOGY

The fibers extracted from the bast of prosopis juliflora and subjected to alkali treatment using NaOH at 5% concentration was used after crushing it in to finer form. Glass fiber bidirectional woven roving mat of 610gsm and jute fiber mat of 367gsm were used. Vinyl ester resin was used as matrix and chemical compounds such as cobalt naphthanate, methyl ethyl ketone peroxide and dimethyl amine were used as acceralator, catalyst and promoter. Out of Seven types of laminates, four were of sandwich type with prosopis fibers placed between layers of glass and jute fiber mats, one was prepared using only prosopis fibers and the remaining two were made using alternate layers of jute and glass fiber mats in 0°, 90° and 45° orientations. The tensile test was carried out using TUN 400 universal testing machine by adopting the dimensions and standards stipulated in ASTM 638. During the test, the cross head speed was maintained at 5mm/min. The extensometer was mounted at the centre of gauge length of the specimen to observe the

change in length experienced by the specimen during the test. The dimension of flexural test specimen and the procedure adopted for the flexural test was carried out as per ASTM 790. The span of the specimen was kept as 120mm. The specimens were subjected to point load at the centre and the corresponding deflection was measured using dial gauge of 0.01mm accuracy.

IV. RESULTS AND DISCUSSIONS

The uniformity in distribution of prosopis fibers in the core layer held between two layers of glass fiber mats has resulted in better stress transfer compared to specimen GPJGPJG where in prosopis fibers sandwiched between three layers of glass fiber mats.

Tensile Strength

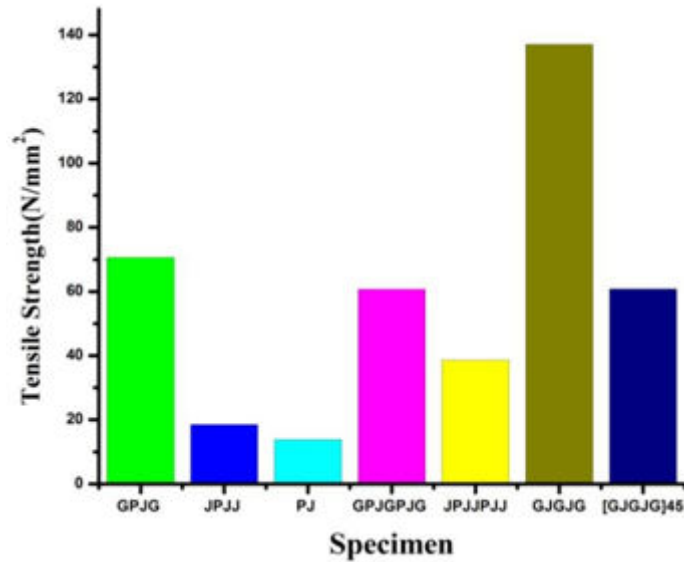
From Table 1 and Graph 3, it is evident that the specimen GJGJG with alternate layers of jute and glass fiber mats in 0° and 90° orientations was found to have maximum tensile strength of 137.045MPa. The presence of glass and jute fibers along the direction the tensile load has resulted in appreciable increase in tensile resistance. The next highest tensile strength was observed in specimen GPJG where prosopis fibers sandwiched between two layers of glass fiber mats.

Table 1: Test results of specimens

Specimen	Layup Code	Tensile Strength (N/mm ²)	Flexural Strength (N/mm ²)	Energy Absorption (Joules)	Percentage of Water absorption
GPJG	Glass/PJ/Glass	70.65	185.38	7.30	0.78
JPJJ	Jute/PJ/Jute	18.54	182.25	2.70	2.30
PJ	PJ	13.80	91.34	7.0	0.43
GPJGPJG	Glass/PJ/Glass/PJ/Glass	60.70	198.99	10	0.44
JPJJPJJ	Jute/PJ/Jute/PJ/Jute	38.54	176.50	6.80	1.80
GJGJG	Glass ₀ /Jute ₉₀ /Glass ₀ /Jute ₉₀ /Glass ₀	137.05	316.51	15.30	0.48
[GJGJG] ₄₅	Glass ₄₅ /Jute ₄₅ /Glass ₄₅ /Jute ₄₅ /Glass ₄₅	60.80	272.42	18	0.52

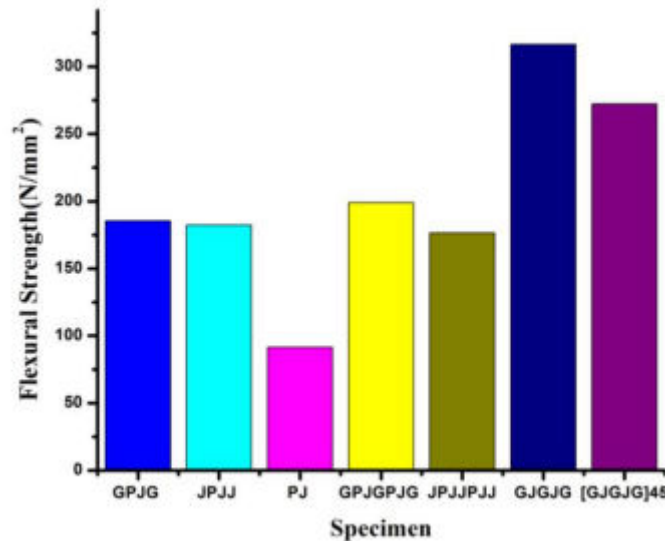
Flexural Strength

From the Graph 3, it can be observed that specimens GJGJG and [GJGJG]₄₅ were found to have maximum flexural strength compared to other specimens. When the specimen is subjected to bending, stress transfer between the layers of fiber mats occur through shear.



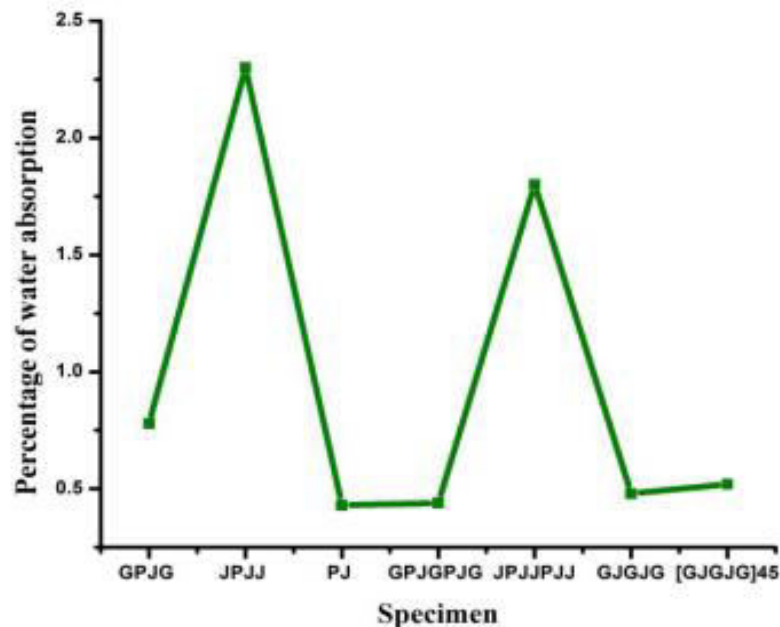
Graph 1: Plot of Tensile Strength

The presence of glass and jute fibers in mat form enhances the flexural resistance substantially. However, all the sandwich specimens containing prosopis was found to exhibit good flexural resistance. The fiber continuity in the core layer has resulted in better stress transfer from mid region to the supports. The lowest flexural strength was reported for specimen PJ containing only prosopis.



Graph 2: Plot of Flexural Strength

A similar trend was observed in the study wherein chopped banana and sisal fibers were used as sandwich between two and three layers of glass fiber mats.



Graph 3: Plot of percentage of water absorption

The tensile strength of banana fiber sandwiched and sisal fiber sandwiched two layer glass fiber specimens was found to be higher than three layered glass fiber sandwiched specimens.

The interweaving of prosopis fibers while mixing them intimately with the polymer matrix has abruptly improved its impact strength. Although the tensile and flexural strength of specimen PJ was considerably lower than other specimens, its impact strength was found to be good and comparable with glass fiber reinforced specimens.

V. CONCLUSION

The utilization of composite materials offers significant opportunities to achieve lightweight structures while maintaining the necessary mechanical properties. The mechanical properties of prosopis sandwiched glass and jute fiber reinforced specimens were studied and compared with specimens reinforced only with prosopis and with glass/jute fibers in alternate layers. The efficiency of stress transfer between prosopis fibers present in the core layer to the glass fiber at the periphery was found to decrease with increase in sandwich layers. The findings of this research have implications for industries seeking to enhance the efficiency, performance, and sustainability of their products. The variation of impact resistance showed a different trend with specimen containing only prosopis exhibited higher energy absorption when subjected to impact load. By considering the potential of composite materials and employing effective analysis and optimization techniques, mechanical engineers can push the boundaries of lightweight design and contribute to a more sustainable and advanced future. The optimal number of roof layers is determined through this process. Finally, the CFRP roof is established in Fibers software, and simulation analysis is employed to compare and verify the performance of the roof before and after optimization.

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