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Statistical and Numerical Optimization of Lightweight GFRP Textile Biobased Multilayered Beams Under Uniform Bending

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Abstract:

This study adopts a general approach to the statistical and numerical optimization of lightweight beams made from glass fiber-reinforced polymer (GFRP) textiles skins and a honeycomb core, specifically under uniform bending conditions. Using integrated experimental data with finite element analyses (FEA), the assessment of the mechanical performance and structural efficiency of the beams are carried out. The response surface methodology (RSM) to design the critical variables such as fiber orientation, textile and thickness that influence load-bearing capacity and deflection. The optimization outcomes demonstrate notable enhancements in performance metrics, resulting in the creation of lightweight multilayered beams that maintain structural integrity while reducing material consumption. The findings show a positive correlation and agreement with the second order combination factors and the emphasized bending loads and provide an optimal design of GFRP-based multilayered beams.

Keywords — **GFRP-based beams, Optimization, Statistical modelling, FEA, Uniform bending.**

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I. INTRODUCTION

The study of multilayer multilayered structures has gained significant attention due to their unique mechanical properties and lightweight design, making them suitable for various engineering applications. Recent research highlights the anisotropic behavior exhibited by these structures during bending, which necessitates advanced nonlinear modeling techniques for accurate performance predictions [1-3]. Growing demand for sustainable and efficient construction practices has prompted researchers and engineers to explore innovative materials and design methodologies. One such advance is the use of fiber-reinforced polymer (FRP) composites in lightweight engineering structures. FRPs offer high strength-to-weight ratios, excellent corrosion resistance and enhanced durability, making them an ideal choice for modern engineering applications [4]. Integrating FRPs not only improves structural performance, but also contributes to weight reduction, facilitating handling and transportation [5]. In addition, lightweight FRPs enables more efficient structural designs, reducing material requirements and associated costs [6].

Despite these advantages, challenges remain regarding the widespread adoption of FRP materials in construction. Issues such as adhesion between FRPs and beams components, sensitivity to temperature variations and long-term durability under varied environmental conditions require further research [7-10]. In this respect, the growing interest in sustainable materials has spurred research into biobased cores for multilayer multilayered structures, valued for their mechanical advantages and ecological benefits. Recent investigations have revealed the anisotropic bending behavior of these structures, highlighting the need for nonlinear modeling to accurately assess their performance [11, 12]. This article explores the intricacies of modeling the mechanical response of biobased core materials, filling existing gaps in the literature and providing a foundation for future inquiries. By employing advanced computational methods, deeper understanding of the ultimate performance of these cutting-edge materials facilitating their use in engineering and design is achieved [13-18].

Accordingly, this study aims to develop numerical simulations of a multilayered structure based on a natural fiber to enhance the understanding of mechanical behavior. The implemented numerical approach sheds light on the significant importance of all the studied parameters in the final response to compression. The effectiveness of the nonlinear local approach depends on several factors, such as the strength of construction materials, joint properties, and containment material properties. As a primary conclusion, the results of this research could have significant practical implications, especially in improving design and construction practices. By providing detailed information on the mechanical performance of the multilayered structure, the various results demonstrate the effectiveness of the proposed model in predicting the structure's resistance and deformability. Overall, the results show enhanced thermal insulation performance in all specimens compared to values reported in the literature for multilayered core materials.

II. BACKGROUND AND NLFEM

The geometric model and the choice of finite element models for the mesh are generated in a three-dimensional (3D) space, taking into account the experimental behavior of the constituent materials. Numerical results in terms of observed and overall behavior are highlighted and validated with a high correlation on the basis of exciting literature works.

The simulated multilayered beam depicted in Fig. 1 presents the following dimensions: The skin: 1 mm thickness, 550 mm length, 45 mm width. The core: 40 mm thickness, 550 mm length and 45 mm width. The core cell: 45° angle, t = 2 mm thickness, 5 mm transverse length and 7.07 mm longitudinal length.

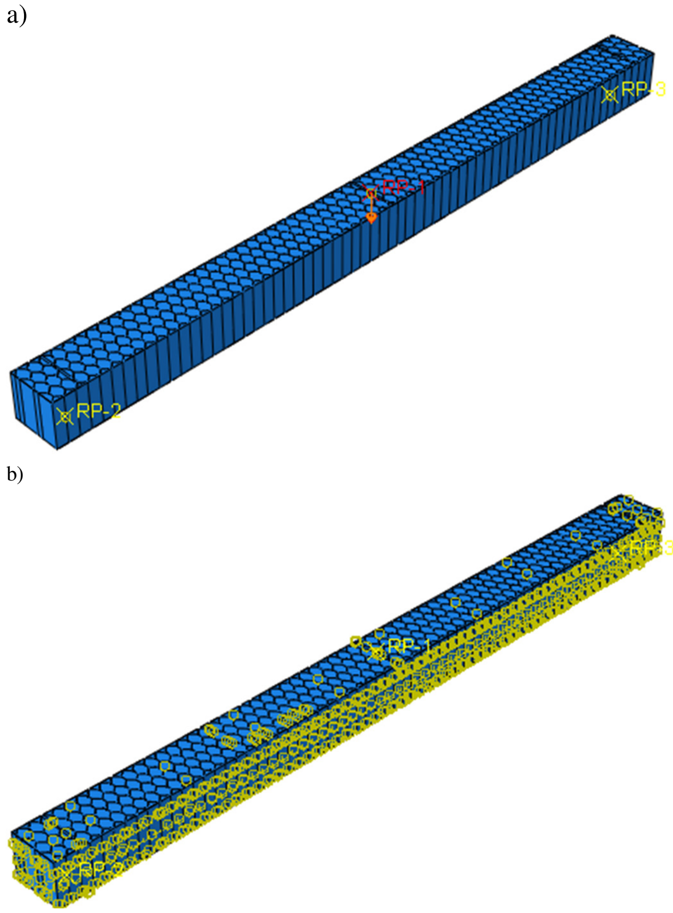

Fig 1. Modeling of the multilayered beams: a) Skins and core assembly, b) Loading setup and interaction.

A. Materials modeling

The composite skins used in our study consists of a set of unidirectional filaments crossed at 90° with three orthogonal planes.

Its orthotropic behavior under the plane stress assumption is described by introducing the stiffness constants given in Table I.

TABLE I
PARAMETER VALUES OF GFRP FABRIC MODEL [21, 26].

E1 (MPa)	E2 (MPa)	G12 (MPa)	G13 (MPa)	G23 (MPa)	Nu12
82000	13600	450	420	400	0.31

However, elastoplastic model for the core as anisotropic elastoplastic behavior in compression and in traction was used. The elastic and post-elastic parameters of the numerical model or under the plane stress assumption are introduced.
Vegetables have a network of cells that provide rigidity and stability. This cellular structure can help maintain the shape of the sandwich, preventing collapse. A well-layered arrangement of different vegetables can create a stable matrix. For instance, stacking denser vegetables at the base and lighter ones on top can improve overall stability. The anisotropic behavior of used biobased core is described by introducing the parameters given in Table II.

TABLE II
POST-ELASTIC AND ELASTIC TENSILE PARAMETERS OF USED CORE.

Yield stress (MPa)	Striction stress (MPa)	Strain at striction stress (%)	Collapse stress (MPa)	Strain at collapse stress (%)
17.84	27.57	1.87	23.77	2.12

B. Finite elements modeling and loading

The honeycomb core was modeled using a 3D hexahedral element of eight nodes (HEX8, ABAQUS elements C3D8) and the rigid plate is modeled using a 3D rigid element with four nodes (R3D4). Therefore, the FRP composites were modeled using 4-node shell elements (S4R). The C3D8 FEMs are coupled with the S4R ones with the Tie function. Accordingly, FRP-to-core bond slip are assumed to be perfect.

A 03-point bending load was applied at the beam midspan under imposed displacement. A monotonic thermal loading was also applied to the upper skin of the modeled multilayered structures. The different test methods used for honeycomb multilayered composites and composite constructions laminated are carried according to ASTM C273-94 (1999) [19] and ASTM C393-62 (1999) [20].

C. Simulation results

The maximum force of the proposed NIDA multilayered beams model is 3764.59 N, while structures tested by [12 – 13] have experimentally obtained maximum resistances of the order of 3000 N. The evolution of the Von Mises stress and logaritmic stain in the web-core and facesheets separately from honeycomb multilayered beams under mechanical bending loading are respectively shown in Fig. 2.

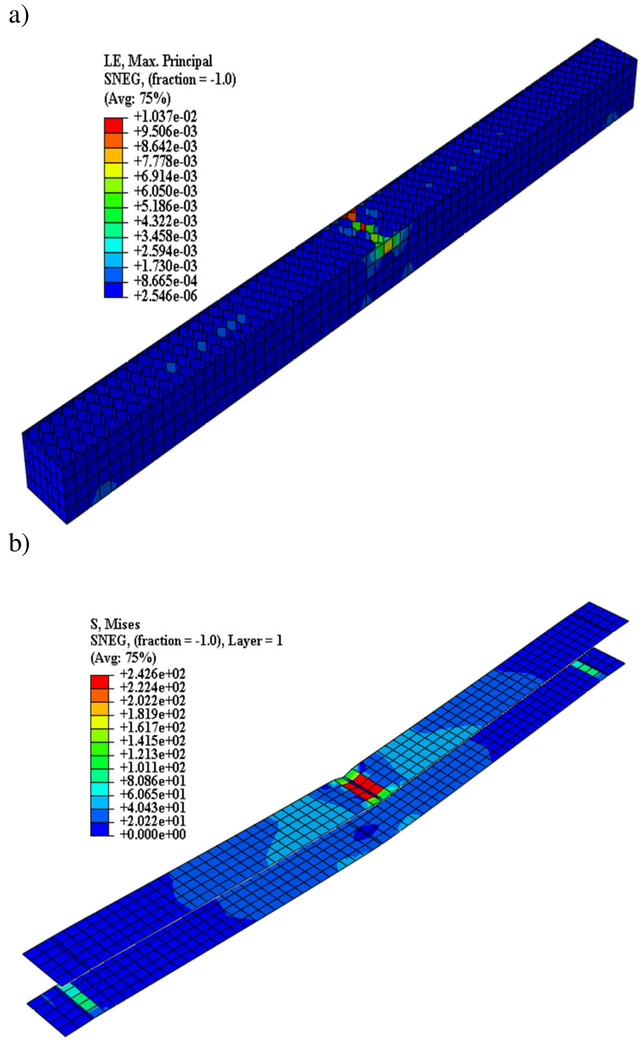

Fig. 2 Stress propagation in (a) the skins and (b) the core of NIDA multilayered beams.

Fig. 2 shows that the stress field first appears in the lower skin compared to the core, then propagates at a very high speed in the core until failure.

The multilayered structures present a certain degree of resistance and ductility. The stress field is located at the level of the upper skin (compressed zone), the analyzed element subjected to a mechanical loading experiences a widely reduced stress field propagation rate.

III. DESIGN AND STATISTICAL CLASSIFICATION

In the quest to optimize the geometrical features of multilayered beams, a Design of Experiments (DOE) approach presents a systematic methodology to evaluate the influence of various parameters on beam performance. This experimental framework allows for the exploration of multiple design variables, such as core thickness, face sheet material, and overall beam geometry, while minimizing the number of experiments needed. By applying factorial or response surface methodologies, we can efficiently identify the interactions between these factors and their effects on critical performance metrics, including bending strength, stiffness, and weight.

As main results, Fig. 3 ddisplays the Pareto chart of standardized effects, while, Fig. 4 illustrates the Henry's half-line of standardized effects, for a 95% interval of confidence.

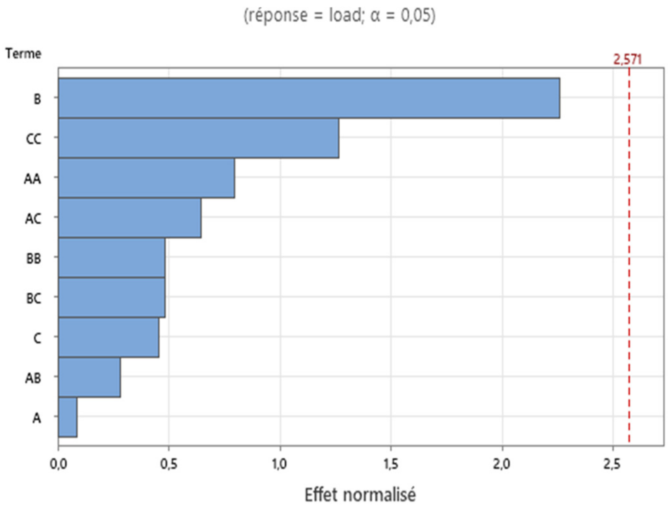

Fig. 3 Pareto chart of standardized effects.

Based on the analysis, suggest actionable steps. This could involve focusing on optimizing the top contributing factors or conducting further studies to understand the minor factors better. Summarize the key insights gained from the Pareto chart and their relevance to the broader context of your research or application, reinforcing the importance of data-driven decision-making. Accordingly, the correlation between the studied factors and the corresponding ultimate load in provided in the radars of Fig. 5. For a 5% error margin, a positive correlation and agreement with the second order combination factors and the emphasized bending loads. Indeed, high values were recorded for when the beams core achieve high thickness and the corresponding span was arranged between 50 and 70 cm.

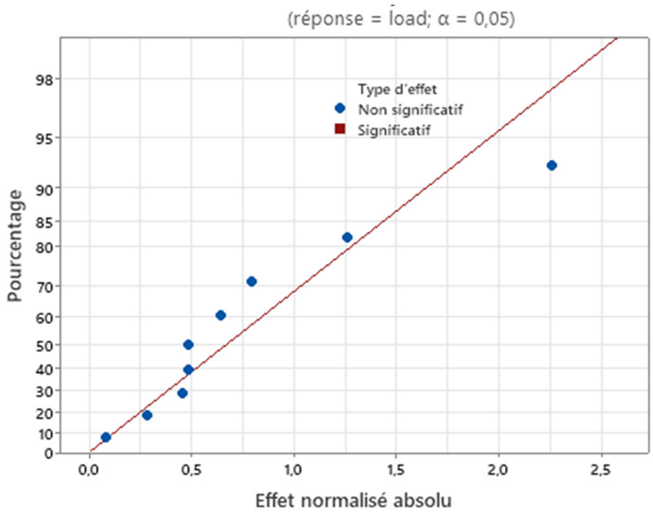

Fig. 4 Henry's half-line of standardized effects

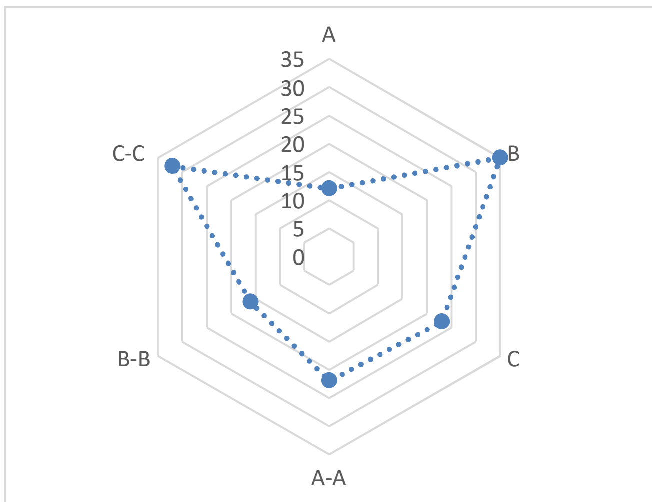

Fig. 5 A radar chart model illustrating the correlation between the studied factors and the corresponding ultimate loads

IV. CONCLUSIONS

The use of the biobased core in multilayered beams has as a direct result a significant reduction in the weight of the structure, thanks to the hollow core design. The different results obtained from the simulation show good agreement with the experimental results taken from the literature. They show the efficiency of the proposed model in terms of strength and deformability prediction. Indeed, the analysis of these results, in terms of overall behavior (force-displacement curves) and local behavior (visualization of stress / strain maps) made it possible to draw the following conclusions:

The biobased multilayered beams present a good threshold of resistance and deformability under mechanical loading, having regard to previous work. This is subject by the combination of mechanical performance of composite fibers;

A significant reduction in deformations and its speed of propagation under mechanical loading, which gives this design good thermal insulation.

In future works, authors suggest to conduct comprehensive experimental studies to characterize the mechanical properties of biobased core materials, focusing on their anisotropic behavior under different loading conditions. In addition, develop and validate advanced finite element models that incorporate nonlinear material behavior and failure mechanisms specific to biobased cores.

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