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Structural analysis of a slotted flap redesigned with composite materia

Análisis estructural de una aleta ranurada rediseñada con material compuesto

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Abstract

This research focuses on assessing the mechanical strength feasibility of utilizing composite materials in the design of slotted flaps as a replacement for isotropic materials. Modern computational capabilities and software tools enable the analysis of both anisotropic and isotropic materials. However, it is imperative to consider several factors to ensure that the computational model accurately mirrors real-world scenarios. In the context of composite materials, this necessitates the comprehensive integration of anisotropic properties such as Young's modulus in different orientations, Poisson's coefficients, fiber orientation, and ply stacking. Additionally, precise delineation of each boundary condition and exploration of various simulation conditions are vital to prevent biases. To validate the developed models, they are rigorously compared with laboratory tests, establishing a robust basis for the obtained results.

Keywords: Structural Analysis; Finite Element Method; Composites; Aluminium alloy; Flap; Aircraft.

Resumen

Esta investigación se centra en evaluar la viabilidad en términos de resistencia mecánica de utilizar materiales compuestos en el diseño de solapas ranuradas como reemplazo de materiales isotrópicos. Las capacidades computacionales y herramientas de software modernas permiten el análisis tanto de materiales anisotrópicos como isotrópicos. Sin embargo, es imperativo considerar varios factores para asegurarse de que el modelo computacional refleje con precisión situaciones del mundo real. En el contexto de materiales compuestos, esto requiere la integración completa de propiedades anisotrópicas como el módulo de Young en diferentes orientaciones, coeficientes de Poisson, orientación de fibras y apilamiento de capas. Además, es vital delinear con precisión cada condición de contorno y explorar diversas condiciones de simulación para evitar sesgos. Para validar los modelos desarrollados, se comparan rigurosamente con pruebas de laboratorio, estableciendo una base sólida para los resultados obtenidos.

Palabras clave: Análisis Estructural; Método de Elementos Finitos; Materiales Compuestos; Aleación de Aluminio; Solapa; Aeronave.

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1. Introduction

Using composites instead of alloy aluminum is a common practice since more than twenty years ago in the aerospace industry [1], [2], [3] Composites are lighter than metals and fiber-reinforced materials such as carbon fiber are more resistant and have a good fatigue performance [4]. Carbon fiber reinforced plastic (CFRP) has been explored for the usage in aircraft skin panels [5]. The use of computational models to carry out structural analysis reduces costs and time in several applications like the aerospace and automotive industry [5], [6], [7]. Their versatility, robustness, and computational efficiency make them well suited for the real-time, large-scale aircrafts, structures, and habitat applications [8], [9]. One of the most widely utilized numerical techniques is the finite element method (FEM), which allows to adequately represent the stresses and strains that occur in mechanical components [11], [12], characterize complex material behavior [13], and it is suitable for complex geometries such as that of the flaps [14]. With the results of the simulation, it is possible to identify the critical points in the design of the components and if the selected material would have the right properties for manufacturing these parts [15]. The finite element method has been used to analyze different aeronautic components such as fuselages [16], the shape of bulkheads [17], wings [18], and flaps [19]. The results of the numerical analysis allow implementing failure theories to predict safety factors or weak points in the design [20].

In the design of a new generation drone, two alternatives were considered to design the flaps. Flaps are traditionally used to improve the takeoff and landing aerodynamic performance of aircraft [21]. Initially, the flaps were designed using 0.02 mm aluminum alloy sheets, then a redesign was proposed with the objective of weight reduction. The new design was made using carbon fiber reinforced polymer and a low-density foam core [22]. Both designs were evaluated by means of experimental and numerical analysis, the results were compared to assess the numerical approach and perform further testing. The displacement field is suitable to compare the numerical results with experimental analysis [23]. Measures of displacements in the design under defined boundary conditions are useful to estimate the certainty of the simulation. A total of 9 different loads were implemented from 10 N up to 90 N, the loads were distributed uniformly over the skin of the flap. In the experimental analysis, a pulley system was used to simulate the force.

2. Materials and methods

2.1. Flap geometry and materials

The geometry of the flap made of aluminum alloy is slightly more complex than the one made of composites. The flap made of aluminum is built with a 0.02 mm sheet. The ribs, skin, and spar were manufactured using cutting and folding operation over this sheet, and joint using rivets. Figure 1 shows main component of the flap.

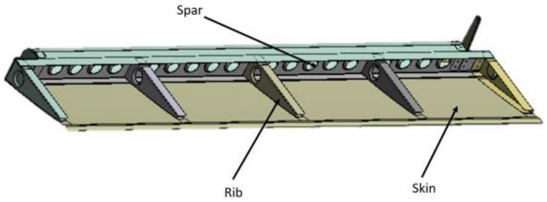

Figure 1. Flap components.

The flap made of composite materials is simpler and it is designed to keep functionality of the flap while reducing weight. The skin is made with two sheets of unidirectional carbon fiber, while the structural components are made with glass fiber and a low-density foam core. Figure 2 shows this configuration.

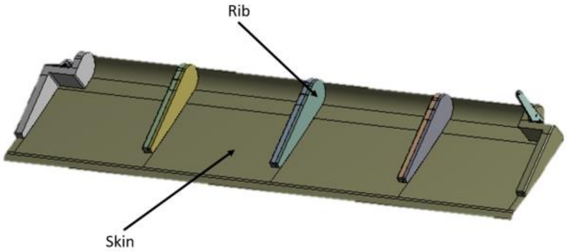

Figure 2. Flap made of composites.

2.2. Problem statement and finite element formulation

The analysis through the FEM is an alternative solution to the theoretical methods and can be implemented for components with complex geometry. As the theoretical calculations of the components made of composite materials are even more difficult than in other materials, sometimes impossible, FEM can be a useful and reliable substitute in the resolution of complex problems [24]. For a displacement-based finite element solution, the principle of virtual work states that the equilibrium of the body requires that for any compatible small virtual displacements imposed on the body in its state of equilibrium, the total internal virtual work is equal to the total external virtual work [25].

Let us consider the 2D linear elasticity problem. The unknown displacement field $\mathbf{u}$, taking values in $\Omega \subset R^2$, is the solution of the boundary value problem given by

$$
\begin{aligned}
-\nabla \cdot \boldsymbol{\sigma}(\mathbf{u}) &= \mathbf{b} && \text{in } \Omega && (1)\\
\boldsymbol{\sigma}(\mathbf{u}) \cdot \mathbf{n} &= \mathbf{t} && \text{on } \Gamma_N && (2)\\
\mathbf{u} &= \mathbf{0} && \text{on } \Gamma_D && (3)
\end{aligned}
$$

where Γ_N and Γ_D represent the Neumann and Dirichlet boundaries with $\partial\Omega = \Gamma_N \cup \Gamma_D$ and $\Gamma_N \cap \Gamma_D = \emptyset$. The Dirichlet boundary condition in (3) is taken homogeneous for simplicity. The weak form of the problem reads: Find $\mathbf{u} \in V$ such that:

$$\forall \mathbf{v} \in V \quad a(\mathbf{u}, \mathbf{v}) = l(\mathbf{v}), \tag{4}$$

where $V = \{\mathbf{v} \mid \mathbf{v} \in H1(\Omega), \mathbf{v}|\Gamma D(\mathbf{x}) = \mathbf{0}\}$ is the standard test space for the elasticity problem, and

$$
\begin{aligned}
a(\mathbf{u}, \mathbf{v}) &:= \int_\Omega \boldsymbol{\sigma}^{\mathrm{T}}(\mathbf{u})\boldsymbol{\varepsilon}(\mathbf{v})d\Omega\\
&= \int_\Omega \boldsymbol{\sigma}^{\mathrm{T}}(\mathbf{u})\mathbf{D}^{-1}\boldsymbol{\sigma}(\mathbf{v})d\Omega \qquad (5)\\
\mathrm{l}(\mathbf{v}) &:= \int_\Omega \mathbf{b}^{\mathrm{T}}\mathbf{v}d\Omega + \int_{\Gamma \mathrm{N}} \mathbf{t}^T\, \mathbf{v}d\Gamma
\end{aligned}
$$

where $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ denote the stresses and strains, and $\mathbf{D}$ is the elasticity matrix of the constitutive relation $\boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon}$. Laminated composite materials are orthotropic materials, they have three axes of symmetry where mechanical properties remain constant.

2.3. Finite element approximation

Let $\mathbf{u}^h$ be the finite element approximation in (6), where N_i represents the shape functions associated with node i and I is the set of all the nodes in the mesh.

The solution lies in a functional space $V^h \subset V$ associated with a mesh of isoparametric finite elements of characteristic size h, and it is such that $\forall \mathbf{v} \in V^h$, $a(\mathbf{u}^{\mathrm{h}}, \mathbf{v}) = l(\mathbf{v})$.

Using a variational formulation of the problem in (1–3) and the finite element approximation $\mathbf{u}^{\mathrm{h}} = \mathbf{N}\mathbf{u}^e$, where $\mathbf{N}$ denotes the basis polynomial functions of second order, we obtain a system of linear equations to solve the displacements at nodes $\mathbf{u}^e$:

$$\mathbf{KU} = \mathbf{f} \tag{7}$$

where $\mathbf{K}$ is the stiffness matrix, $\mathbf{U}$ is the vector of nodal displacements and $\mathbf{f}$ is the load vector. The steps for the finite element analysis include definition of the boundary conditions, analysis type, mesh generation, post-processing, results, and analysis of results. A mesh independence test is conducted to ensure the convergence of the solution in displacements.

For the problem under consideration, a linear static analysis with a direct solver is suitable to evaluate the behavior of the flaps, under the imposed boundary conditions. For a linear analysis, the displacements are solved under the following assumptions: The stiffness matrix $\mathbf{K}$ is essentially constant, such that the materials have linear elastic behavior and small deformations theory is used. The load vector $\mathbf{f}$ is statically applied, i.e., no time-varying forces are considered, and no inertial effects are included.

2.4. Boundary Conditions

The experimental analysis is formulated using a simple setup, but it represents a critical operation condition of the flap. The component was fixed using a bearing and a fixed point in the angle of attack as shown in the Figure 3.

Figure 3. Boundary conditions.

A vertical distributed force is applied over the attack angle and the skin as shown in Figure 4. This force increases from 10 N up to 90 N. In the experimental analysis, the displacement was measured in several points [22]. In a specific point across the horizontal middle of the skin, the displacement was compared between experimental and numerical approaches.

3. Numerical results

3.1. Aluminum alloy flap

The first flap is made with aluminum alloy, with an elastic modulus of $E = 71000$ MPa. This flap is heavier than the one made with composites, and it is more complex because there are components with many holes and changes of geometry due to sheet folding and cutting. The stress field was analyzed to evaluate the factor of safety using the Von-Mises equivalent stress after performing mesh independence tests for the displacement solution.

Figure 5 shows the stress distribution over the flap. The max. force applied caused a von Mises stress over 361.8 MPa meanwhile the min. force originated a maximum equivalent stress over 48 MPa.

The safety factor decreased from 12 to 1.1 with the min and max force, 10N and 90N respectively. Figure 6 shows the variation of the factor of safety for each load applied.

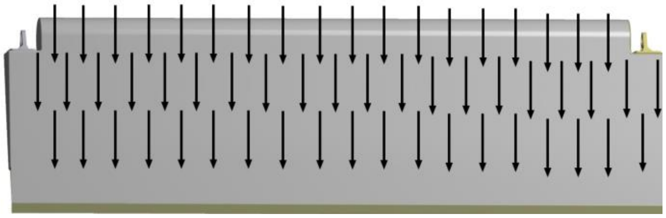

Figure 4. Loads over the flap.

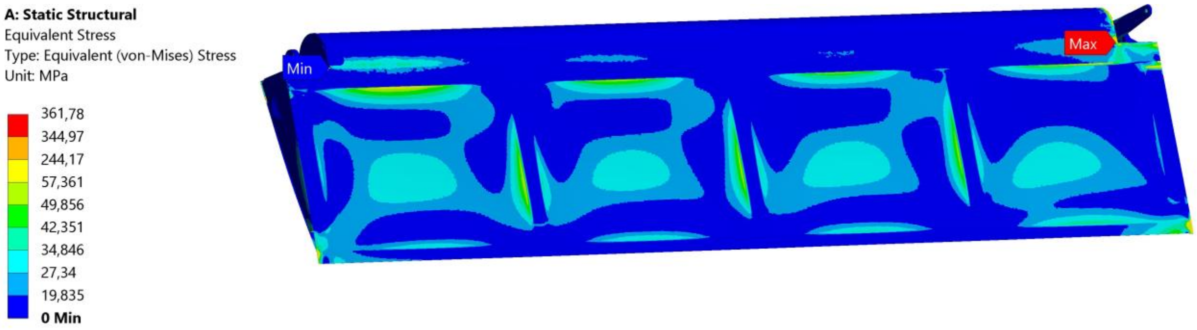

Figure 5. Stress field over the flap.

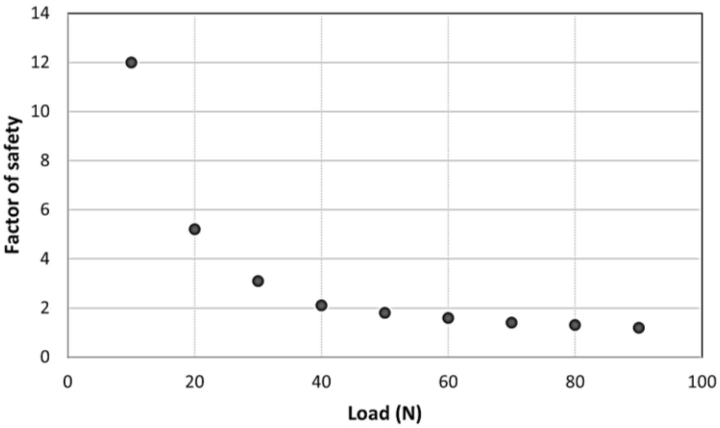

Figure 6. Factor of safety.

Vertical displacement was measured in the experimental and numerical approaches. With the purpose of validate the procedure developed the error was calculated and analyzed. The calculated and the experimental displacements for each load are shown in Figure 7.

Ten measurements of vertical displacement were made at a specific point. The maximum displacement measured was about 0.69 mm, while in the simulation a maximum displacement of 0.81 mm was calculated, the average error found was about 17%. Displacements calculated are greater than the experimental ones, the main source of error could be that the counterweights are used to balance the load mast and the saddles. However, the accuracy of the balancing is not perfect and the weight of the load mast itself could affect the measurement.

3.2. Flap made with composites

The composite structure is lighter than the aluminum flap, with a weight reduction of 18 %. The unidirectional fiber carbon has an elastic modulus of E_1 = 2090000 MPa in the fiber direction, and E_2 = E_3 = 9450 MPa in the transversal directions. The low-density foam used in the core has an elastic modulus of E = 70 MPa and a Poisson ratio of 0.3. The procedure to evaluate the flap made with composites is similar to the one shown for the flap made with aluminum alloy. However, it was not possible to assess the flap with failure criteria because there is not enough available data to carry out those analyses. Figure 8 shows the stress field, stress distribution is similar to the one obtained in the aluminum alloy flap. The values of stress change due to the material models used.

The vertical displacements calculated and measured in the experimental test were slightly larger. Figure 9 shows the displacements for each load for both numerical and experimental approaches. The mean error found was about 20%. However, both curves have similar behavior, and in the smaller forces, the error is about 5%.

4. Conclusions

The evaluation of flaps constructed from conventional materials such as alloy aluminum and composites was conducted through a combined experimental and numerical investigation.

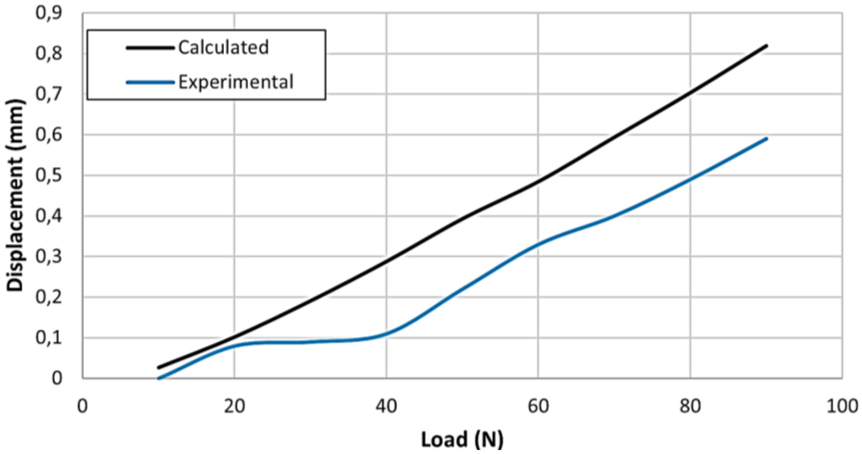

Figure 7. Vertical displacements.

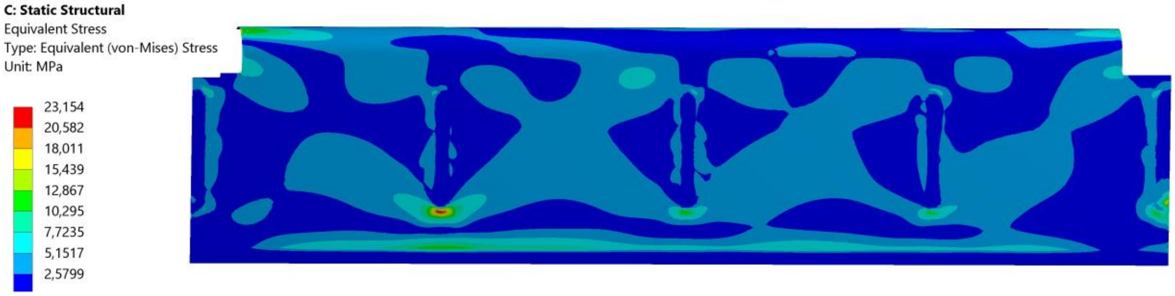

Figure 8. Stress field over the flap made of composites.

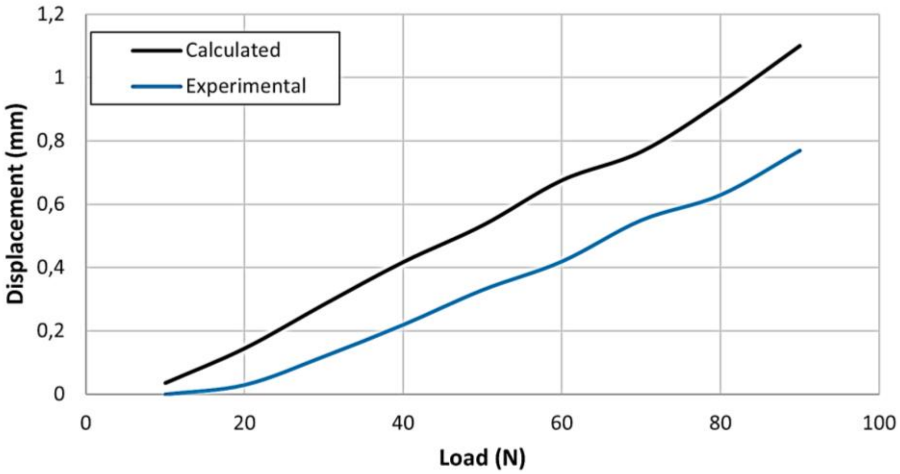

Figure 9. Vertical displacements vs. the load for experimental and numerical models.

The findings from these analyses affirm that both design approaches are capable of withstanding operational loads effectively.

To ascertain the applicability of a numerical approach in future research, a static analysis was undertaken. This analysis was executed using Finite Element Analysis implemented within commercial software. To ensure solution robustness irrespective of mesh size, an assessment of mesh quality and mesh independence was conducted.

The numerical results were compared with experimental data by assessing vertical displacement at designated points. The observed error in both design variants falls within acceptable limits, thereby underscoring the reliability of employing numerical methods as a prelude to prototyping.

The use of composite materials, as opposed to traditional materials, facilitated a noteworthy reduction in the weight of mechanical components while only marginally affecting mechanical performance. This weight reduction amounted to approximately 60 g, translating to a 20% decrease relative to the initial weight. Nonetheless, it's worth noting that the adoption of these materials, along with the associated manufacturing processes, design intricacies, and numerical analyses, does introduce some added complexity, leading to associated incremental costs.

Autor Contributions

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Autor Contributions

S.A. Ardila Parra: Investigation, Conceptualization, Investigation, Methodology, Writing –original draft. J. J. Barba-Ortega: Conceptualization, Methodology, Writing –review& editing. O.A. González-Estrada: Supervision, Funding acquisition, Resources, Investigation, Conceptualization, Methodology, Writing –review& editing.

All authors have read an agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Institutional Review Board Statement

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Informed Consent Statement

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