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Review on Stress Analysis and Optimization Technique for Composite Wing Rib with Cut-Outs

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Abstract: This review paper comprehensively studies stress analysis and optimization techniques for composite wing structures with cut-outs primarily wing rib. It emphasises the significance of weight reduction in composite structures to ensure economic viability. It explores various methodologies such as Finite Element Method (FEM), Equivalent plate method, topology optimization and Experimental method. The paper discusses the impact of cut-out size, shape, and fibre orientation on stress distribution and structural integrity. It also highlights the need for efficient design procedures, advanced manufacturing techniques, and further research in areas such as the effect of environmental factors on wing rib performance and fatigue analysis. The paper concludes by suggesting future research directions to enhance the design and engineering of composite wing structures.

Keywords: Cut-outs, Stress concentration, Stress optimization, Wing rib.

I. Introduction

Composite wings are wings constructed primarily from composite materials such as carbon fibre-reinforced polymers. Such composites are typically made from layers of different kinds of fibres or other advanced materials embedded in a resin matrix. The fibres can be oriented in specific directions to optimize the wing's performance under various loading conditions. This allows for tailored aerodynamic and structural properties. The composite wing encompasses elements like spars, ribs, skin and stringers. The wing spars are essential structural parts that run parallel to the aircraft's lateral axis, bearing the various loads during flight. Wing ribs work simultaneously with pars and stringers to provide the wing with it cambered shape and assist in load transmission from the wing skin and stringers to the spars. These ribs also help resist pressure loads, particularly when fuel is carried in the wings. While the skin alongside the ribs and spars shares the shearing load induced during flight. Fig. 1 below illustrates the components of the wing structure.

This review paper primarily focuses on wing ribs which comprehensively outline the stress analysis and optimization techniques for composite with cut-outs.

Carbon fibres are used often in the fabrication of wing ribs due to their high stiffness and superior strength-to-weight ratios compared to aluminium. To be feasible, composite wing structures are only viable through significant weight reduction. This requirement for weight reduction necessitates the development of efficient design procedures and advanced

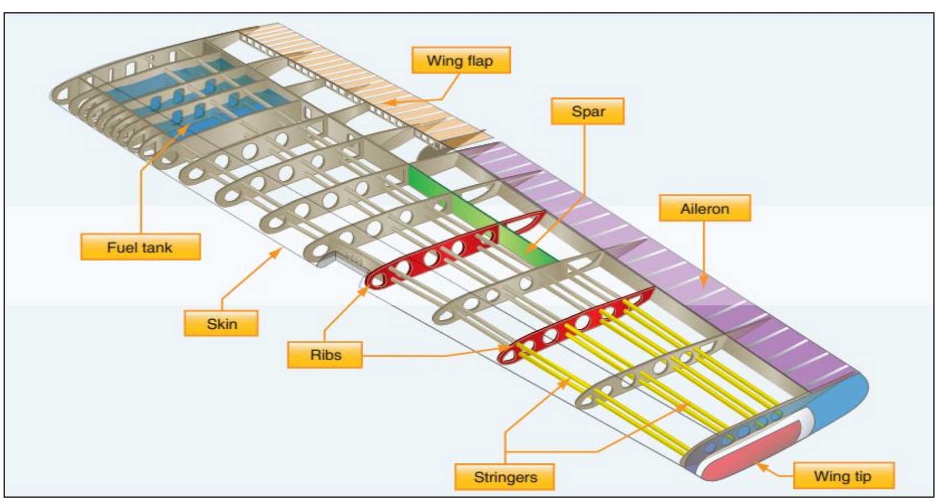

Fig. 1: Basic Aircraft Wing Structure

manufacturing techniques tailored for composite structures. Moreover, introducing cut-outs in composite wing ribs makes composite economically viable and reduces the overall weight of the wing structure. Although cut-outs pose notable challenges concerning stress distribution and structural integrity. These cut-outs can create localized stress concentration, which greatly affects the mechanical strength of the wing. When discontinuities like holes are introduced, they can lead to increased localized stresses that can potentially result in structural failures. Such stress concentration can compromise the rib's capacity under load or the performance of the entire wing structure by hindering the rib's ability to transfer shear loads from the skin to the spur.

Studies indicate that the presence of cut-outs, regardless of their shape negatively impacts the rib's mechanical strength. Specifically, stresses near the cut-out regions are very high, making these regions a critical point for structural analysis. Effective stress analysis and optimization techniques are therefore vital for designing wing ribs with cut-outs, which guarantee the wing to withstand operational loads over its lifespan.

A. Stress Concentration Factor

Plates or shells of numerous assemblies are widely use as the main structural elements in aerospace, mechanical and civil engineering structures. Recently, the increasing need for lightweight effective structures has led to structural shape optimization. Varieties of cut-out shapes in structural elements are required to reduce the weight of the structure and offer access to other parts of the structure. It is well known that the manifestation of cut-outs in a stressed member forms highly localized stresses near the cut-out. The ratio of the maximum stress at the cut-out edge to the nominal stress is called the stress concentration factor (SCF). Understanding of the effects of cut-out on the load bearing capability of the plate is actual vital in designing structures.

Consider the plate displayed in Fig. 2, loaded in tension by a force per unit area Consider that the external dimensions of the plate are infinite associated with the diameter of the hole 2a. It is known, from linear elasticity that the lateral stress all over the plate is given by

$$\sigma\theta = \sigma /2\,[1 + (a\,2/r2) - (1 + 3(a\,4/r4)]\,cos\,2\theta$$

Or

$$\sigma_{max} = \sigma\left(1 + 2\frac{a}{b}\right) = \sigma\left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$

The maximum stress is σθ = 3σ at r = a and θ = -+ 90 degrees. Fig. 3 illustrates how the tangential stress varies along the x and y axes of the plate. For the top (and bottom) of the hole, we see the stress gradient is extremely large compared with the nominal stress, and hence the term stress concentration applies.

Along the surface of the hole, the tangential stress is –σ at θ = 0 degrees and 180 degrees, and increases, as θ increases, to 3σ at θ = 90 degrees and 270 degrees.

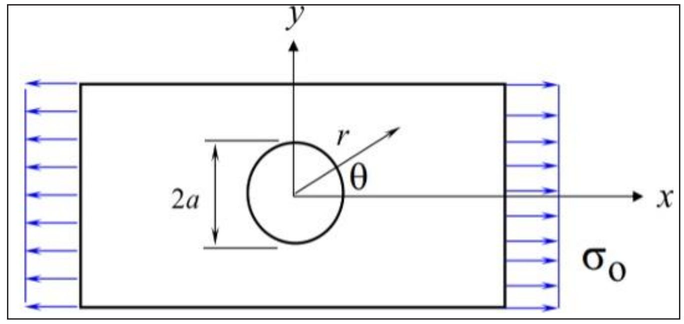

Fig. 2: Plate with Circular Hole Loaded

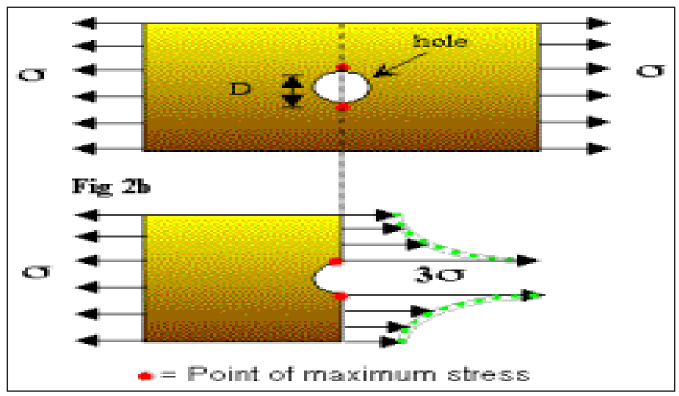

Fig. 3: Tangential Stress Distribution

The static stress concentration factor in the elastic range, Kt, is defined as the ratio of the maximum stress, σmax, to the nominal stress, σnom. That is,

Kt = σmax /σnom

For the infinite plate containing a hole and loaded in tension, σnom = σ, σmax = 3σ, and thus Kt = 3.* The analysis of the plate in tension with a hole just given is for a very wide plate (infinite in the limit). As the width of the plate decreases, the maximum stress becomes less than three times the nominal stress at the zone containing the hole.

The static stress concentration factor for a plate containing a centrally located hole in which the plate is loaded in tension depends on the ratio 2r/D is given by the equation:

Kt = 3.00 - 3.13(2r/D) + 3.66(2r/D) ^2 – 1.53(2r/D) ^3.

II. Literature Review

Different approaches and techniques were employed to analyze and optimize stress distribution on wing rib with discontinuities. The most prominent method used for stress analysis is finite element analysis (FEA), which play a crucial role in assessing stress distribution on structures. By simulating load conditions alongside the structural parameters, FEA can identify areas of high-stress concentration, allowing for targeted design optimizations. This method of analysis offers important understanding into possible points of failure, allowing engineers to improve designs and increase structural integrity prior to manufacturing.

(Ali *et al.,* 2021) [1] focus on the impact of cut-out shapes on stress distribution in aircraft wing ribs using FEA in ANSYS software. They find that elliptical cut-outs optimally reduce weight and stress. However, the study does not consider complex loading situations, cut-out shape or size optimization techniques like fillet and different cut-out orientations, which are crucial when conducting stress analysis, indicating an area for future research.

(Yeh, n.d.) [2] utilizes Anisotropic plate theory to evaluate stress concentration on X-29A carbon fibre composites with circular cut-outs under various loading conditions and fibre orientations. Anisotropic plate theory deals with the behaviour of flat plates that have different material properties in different directions with the assumption that the plate is thin and stress components vary through the thickness of the plate. But not effective for complex geometry. However, the paper lacks a comparison of stress concentration factors among different composites and limits its focus to the impact of fibre orientation alone. (Yeh, 1988) [3] expands on this work by considering the effect of temperature variation on stress concentration factors in X-29A carbon fibre composites and demonstrates that the stress concentration factor varies with temperature and loading direction. However, the study does not examine the effect of high temperatures or extremely low temperatures on stress concentration.

On the other hand, optimization techniques provide best possible solution regarding multiple alternatives and at the same time adhering to certain constraints. The objective is to minimise stress concentrations and maximize structural integrity around cut-outs. Optimization can be achieved by evaluating several configurations, materials and cut-out shapes or by varying parameters such as the layup sequence, Ld ratio or boundary conditions. For instance, equivalent plate method (EPM) is used as a structural analysis technique to simplify the modelling of complex structures, such as composite wing rib with cut-outs, by representing them as equivalent plates. This method reduces the computational complexity while maintaining accuracy.

The equivalent plate method, while powerful has several limitations especially when applied to complex structure like composite rib with cut-outs. Some key limitation like; lack of proper representation for anisotropic materials particularly in complex layup configurations, EPM may not provide the level of detail required for final validation, non-linearity of materials may affects it's accuracy and in region of high stress gradients or complex load path EPM may not accurately represent all the nuances of the actual structure. Despite these limitations, EPM remains a valuable tool for preliminary design and optimization providing a good balance between computational efficiency and accuracy. (Kilimtzidis *et al.*, 2023) [4] presented an optimization framework using the Equivalent Plate Method (EPM) for designing composite aircraft wings. This method demonstrated computational efficiency, accurate prediction of natural frequencies and reduction in wing weight. However, the research did not include explicit constraints for static stiffness, highlighting the need for comprehensive strength evaluations.

Other techniques that enhance structural integrity include fibre steering and topology optimization. Fiber steering refers to the ability to control the trajectory of fiber reinforcement within composite materials. This technology allows for optimized structural designs aligning the reinforcing fibres with the specific load paths a structure experiences. By changing the fibre direction within each laminate, this result in evenly distribution of load across the entire structure mitigating stress concentration. Engineers can improve the mechanical properties of composites by strategically steering the fibers around the cut-outs or discontinuity, resulting in enhanced strength and stiffness without extra weight.

Designing composite structures that incorporate fiber steering presents challenges when dealing with wing ribs that have multiple cut-outs. To effectively utilize fiber steering, a deep understanding of load paths and material properties is crucial. Furthermore, any adjustments to fiber orientation must be executed carefully to avoid unintended increases in panel weight or the creation of structural vulnerabilities. Despite these limitations, this method has proven to be especially successful in aerospace parts, where it is essential to uphold a lightweight structure while guaranteeing excellent structural capabilities. (Zucco *et al.,* 2021) openings for access purposes, or fasteners in the primary structural parts of airplanes. The presence of cutouts in composite panels results in stress or strain concentrations, leading to potentially reduced load-carrying capacity. Steering tows around cutouts using emerging techniques in three-dimensional (3-D) [5] explored the benefits of continuous tow steering around elliptical cut-outs, which improve buckling performance and reduced stress concentrations. This advanced approach showed substantial improvement compared to traditional straight-fibre orientations. However, comparisons with other fibre alignment methods like ply drop-off, were not extensively covered.

Topology optimization is a mathematical method that aims to improve the distribution of materials within a specified design area, while considering factors such as loads and boundary conditions. This approach involves restructuring materials to maximize performance criteria such as stiffness, while simultaneously reducing material consumption, resulting in the creation of more effective and environmentally friendly designs. Topology optimization is important for improving stress distribution in composite wing ribs with multiple cut-outs. Cut-outs can lead to high stress concentration, which may jeopardize the integrity of the wing ribs. Topology optimization strategically reinforces areas around cut-outs while optimizing material removal in low-stress regions to maintain overall strength while reducing weight.

Designing composite wing ribs with multiple cut-outs using topology optimization is challenging. It requires advanced computational methods and expertise to accurately model the complex geometries caused by the cut-outs. Moreover, it's essential to balance material efficiency with structural integrity to ensure that the optimally designed ribs can resist supposed loads without compromising safety. None the less, its application leads to improve performance and efficiency, offering solution for structures with complex geometries and cut-outs. (Hu and Vambol, 2020) [6] uses the SIMP model for topological optimization to enhance wing rib design in lightweight aircraft structures, resulting in over 20% reduction in deformation compared to the unoptimized wing rib. The study did not compare their optimization method with others in the field of composite design, indicating a possible area for future research.

Stress analysis and optimization techniques for composite aircraft structures with cut-outs play a crucial role in enhancing the safety, efficiency, and performance of modern aircraft. This dynamic field combines advanced mathematical modelling, innovative material science, and practical considerations for aircraft design. This review paper aims to explore the latest research developments and their implications for the future of aerospace engineering.

A. Stress Analysis of Composite Wing Structures with Cut-Out

The presence of cut-outs in composite wing structures can result in significant stress concentrations, which can vary based on factors such as the number, size, and arrangement of the cut-outs as well as the configuration of the composite laminate. Several studies have examined the impact of these parameters on stress concentration in composite wing structures under different loading conditions.

The anisotropic stress concentration factor (SCF) in composite materials with circular holes utilises anisotropic plate theory to calculate the SCF for the X-29A composite. The findings reveal that the anisotropic SCF varies with fibre orientation and is not constant across the composite. This inconsistency can have a significant influence on the structural performance of the material. Thus the approach used in the study deviated by 20% from the experimental data (Yeh, n.d.) [2].

Additionally, the effect of temperature on SCF for X-29A composite was examined using anisotropic elasticity theory to determine how SCF changes with temperature variations. The research concluded that SCF decreases as the temperature rises. Two approaches employed to calculate the SCF at room temperature: the mixture rule and the constant strain approach. The latter closely matched the experimental data, while the former was more accurate at low temperatures but deviated at higher temperatures (Yeh, 1988) [3].

Due to the time-consuming nature of stress analysis for aircraft wing structures, a free MATLAB-based software was developed to facilitate stress analysis for cut-outs in an idealised wing. This software allows students or academics to perform stress analysis seamlessly and within a reasonable time frame (Riyadh and Ali, 2018) [7].

B. Effect of Cut-Out Size and Shape

In practice, the effect of cut-out shape and size is considered during the design phase of aircraft wings. Engineers must balance the need for cut-outs with the requirement for structural integrity. By improving the cut-out shapes/size and fortifying techniques, it is possible to maintain the wing's performance while integrating required cut-outs for system integration and weight reduction.

For instance, it was found that elliptical cut-outs on wing ribs reduce weight and are the optimal shape for minimal stress concentration compared to other shapes under aerodynamic loads. The stress analysis was carried out using FEA in ANSYS software (Ali *et al.,* 2021) [1].

The use of cut-outs in wing ribs is known to effectively reduce the weight of the structure, which is crucial for improving the aircraft's performance and fuel efficiency. Lighter components help to decrease drag and enhance lift-to-weight ratios. However, cut-outs can also cause stress concentrations in the wing rib, which may reduce the mechanical strength of the structure and potentially increase the risk of failure under extreme conditions. (Bharath *et al.,* 2020) [8] Research indicates that wing ribs with cut-outs experience higher von Mises stress as the number of cut-outs increases. This suggests that while cut-outs can reduce weight, they may compromise structural integrity if not designed carefully. The research considered wing ribs with and without cut-outs, including circular, elliptical, triangular, and rectangular shapes. The study focused on the impact of these configurations on equivalent stresses and deformation. It aimed to identify the best configuration and material combination based on stress and deformation results (Bharath *et al.,* 2020) [8].

Moreover, SCF is affected by increasing cut-out diameter in carbon and glass fibre composite as seen in Fig. 1 and cut-out diameter can affect displacement which when increased reduces displacement as shown in Fig. 2. Cut-outs affect carbon fibre composite the most due to material properties (Dash *et al.,* 2021) [9].

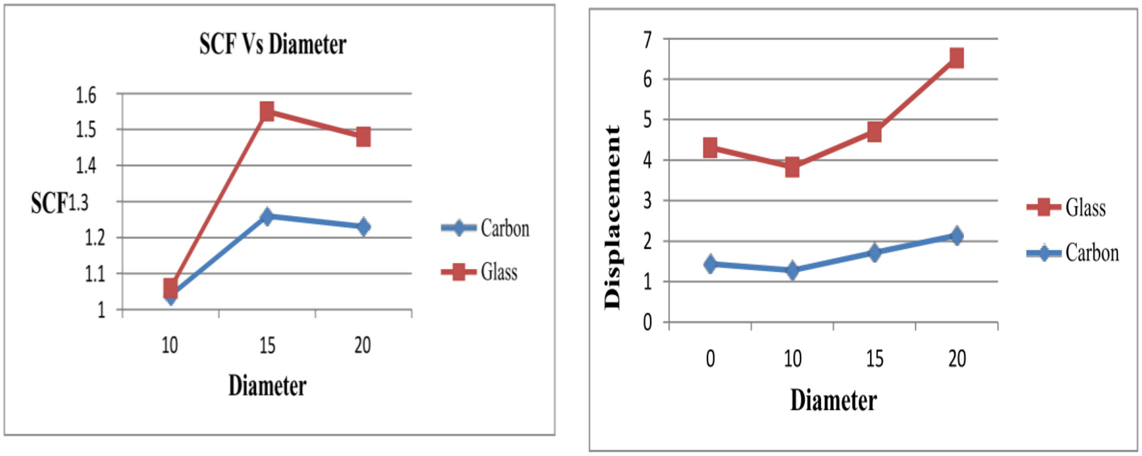

Fig. 4: Effect of Cut-Out Size on SCF and Displacement (Dash *et al.,* 2021) [9]

C. Effect of Fibre Orientation on Cut-Out

Fibre orientation significantly influences the structural integrity and performance of aircraft wing structures. Fig. 5 shows an example of different fibre orientations stacked together to form a composite laminate. They play a role in the determination of mechanical properties such as stiffness, resistance to deformation and damage. Moreover, the fibre direction affects the wing's stiffness, especially in twisting force, which is vital for sustaining the wing's shape and functionality through flight.

Based on stress and deflection criteria for wing rib, different fibre orientations were tested and a comparison was made to determine the best ply orientation, it was found that the ply orientation [0/45/90/90/45/0] offers the best combination of strength and durability for the wing rib design (Kannan and Veeranjaneyulu, 2015) [10], making it suitable for application in aircraft structures. An optimum fibre orientation can intensify the wing's torsional stiffness, thereby improving its resistance to dynamic loads and possible disastrous aeroelastic phenomena such as flutter.

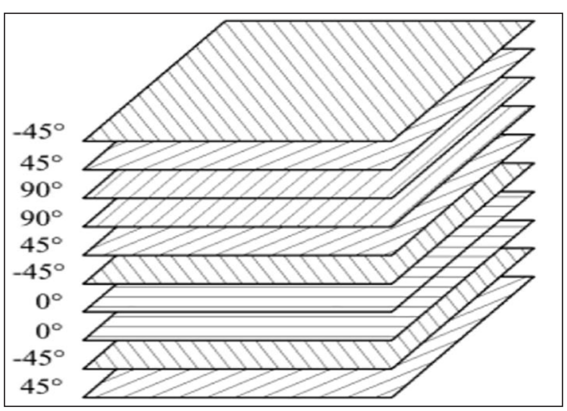

Fig. 5: Different Fiber Orientation Angles

The orientation of fibres around these cut-outs can be enhanced to distribute stresses more evenly and reduce the risk of failure. It is equally important to predict failure mode and stress intensity factor of pre-cracked composite in aircraft structures like the wing rib, under different loading conditions. For instance, a study on Stress intensity factor in pre-cracked composite wing ribs made of carbon-epoxy IM7-8552 on a Boeing-747 rib section with a semi-elliptical surface flaw and circular cut-out under in-plane shear loading with Various crack sizes and locations across layers were analysed using the finite element software ANSYS, to calculate the stress intensity factor for three modes. The result indicates that IM7-8552 shows higher resistance to failure compared to the T300-5208 composite and by modifying the fibre orientation to [45^0/90^0] which shows a tremendous stress concentration reduction (Sivakumar *et al.,* 2016) [11].

Moreover, in a graphite four-layered symmetric laminated rectangular plate with different cut-outs, it was found that when $\theta = 0^0$ (fibre orientation angle) presents minimum SCF in rectangular and circular cut-outs while for elliptical the minimum SCF around the cut-out is when $\theta = 45^0$ (Yasin *et al.,* 2023) impacts the stress concentration factor (SCF) [12].

D. Optimization of Composite Structures with Cut-Outs

Researchers have explored various optimization techniques to moderate stress concentrations. Some of these approaches are fibre-steering, topology optimization, reinforcement and damage tolerance analysis employed to minimize stress concentration and maximize structural integrity around cut-outs. Optimization can lead to changes in cut-out geometry or size, variation in parameters, or combining multiple optimization techniques. Optimization combines advanced mathematical modelling, innovative material science and real-world considerations of aircraft design to improve the safety, effectiveness, and performance of advanced aircraft. This review aims to explore these topics, reconnoitring the latest research progress and their consequence for the future of aerospace engineering. The conventional method of improving stress distribution is through different types of reinforcement methods as shown in Fig. 6 below.

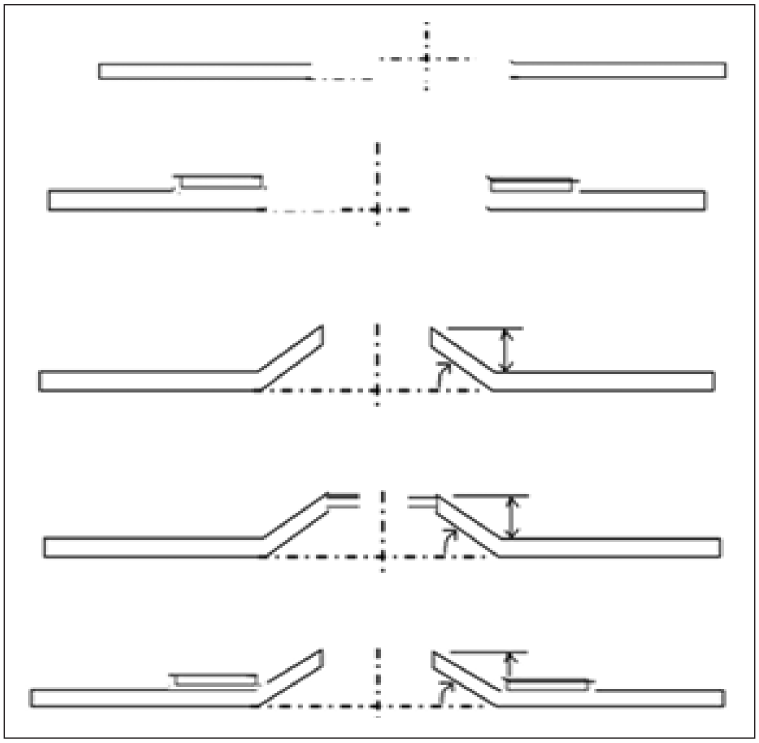

Fig. 6: Type of Reinforcements

Vivekanand Babar presents a numerical study on the effect of reinforcements on circular cut-outs in composite wing ribs under various loading conditions, employing the finite element method with NASTRAN software, the analysis of different reinforcement configurations, such as ring and flange reinforcements, on carbon/epoxy composite was carried out; results indicated that reinforcement significantly reduces stress concentration and enhance buckling loads in composite ribs with flanged cut-outs offer superior load-carrying capacity compared to aluminium counterparts (Babar, 2013) [13].

The advantage of fibre steering of composite laminate over the traditional method is that redistribution of stress is possible without weight penalties. Fig. 7 shows a typical steered fibre composite.

C. Lopes presents a study on the elastic response of composite panels under compression, using finite element analysis to predict the influence of a central circular hole on panel responses. The result shows that the panel failure response is not affected by the presence of a hole due to fibre steering which promotes load redistribution (Lopes *et al.,* 2010) [14].

Fibre-steered panels offer substantial advancement, particularly in terms of first-ply failure loads due to favourable load dispersal. While considering larger cut-outs like windows and doors, parametric numerical studies were used to identify optimal configuration for shear-loaded panels with hole sizes up to two-thirds of the panel, showing that configurations with steered fibre panels outperform straight-fibre panels (Gomes *et al.,* 2014) [15].

Fig. 7: Anisoprint Fibre-Steering Composite

On the other hand, Ronan M. O'Higgins and Paul M. Weaver use the continuous tow steering technology to alleviate stress concentrations around elliptical cut-outs, enhancing bulking performance and reducing strain. The result shows a 26% improvement in bulking load and a significant reduction in stress and strain concentration factor compared to straight-fibre configurations (Zucco *et al.,* 2021) openings for access purposes, or fasteners in the primary structural parts of airplanes. The presence of cutouts in composite panels results in stress or strain concentrations, leading to potentially reduced load-carrying capacity. Steering tows around cutouts using emerging techniques in three-dimensional (3-D) [5]. This approach promises a lower risk of delamination and premature damage, contributing to developing more efficient and resilient composite aircraft structures.

Moreover, reducing the overall weight of the wing as a unit is very important; a study was conducted on streamlining composite wing structures that focus on optimal lay-up sequence for the wing's power components such as ribs, spar, and skin panels under aerodynamic loading. Phyo Wai Aung and Oleg Tatarnikov utilise the Pareto optimization method in selecting a carbon composite wing which could be 60% lighter than the aluminium wing. The FEMAP software package was used for stress-strain and buckling analysis, and optimal fly orientation and component thickness were determined, resulting in significant weight reduction without compromising structural integrity (Aung *et al.,* 2020) [16]. The tables below show the streamlined lay-up sequence of the composite wing components and the best possible combination of lay-up sequences between the wing skin and power component.

Table I: Deflection of the Wing Frame vs Type of Spars and Ribs Laminate Structure (Aung *et al.,* 2020) [16]

Sr. No.	*Spars Laminate Structure*	*Ribs Laminate Structure*	*Deflection*
1	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	34.25
2	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	$+45^0$, -45^0, 0^0,-45^0, $+45^0$	34.27
3	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	90^0, 0^0, 90^0	34.34
4	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	0^0	34.41
5	$+45^0$, -45^0, 0^0, -45^0, $+45^0$	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	25.67
6	$+45^0$, -45^0, 0^0, -45^0, $+45^0$	$+45^0$, -45^0, 0^0, -45^0, $+45^0$	25.74
7	$+45^0$, -45^0, 0^0, -45^0, $+45^0$	90^0, 0^0, 90^0	25.70
8	$+45^0$, -45^0, 0^0, -45^0, $+45^0$	0^0	25.89
9	90^0, 0^0, 90^0	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	28.38
10	90^0, 0^0, 90^0	$+45^0$, -45^0, 0^0,-45^0, $+45^0$	28.36
11	90^0, 0^0, 90^0	90^0, 0^0, 90^0	28.46
12	90^0, 0^0, 90^0	0^0	28.43
13	0^0	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	16.78
14	$\mathbf{0^0}$	$\mathbf{+45^0}$, $\mathbf{-45^0}$,$\mathbf{0^0}$, $\mathbf{-45^0}$, $\mathbf{+45^0}$	**16.77**
15	0^0	90^0, 0^0, 90^0	16.80
16	0^0	0^0	16.81

Table II: Deflation of the Wing vs Skin Laminate Structure (Aung *et al.,* 2020) [16]

Sr. No.	*Skin Laminate Structure*	*Deflection (mm)*
1	$+45^0$, -45^0, 90^0, 0^0, 90^0, -45^0, $+45^0$	84.65
2	$+45^0$, -45^0, 0^0, -45^0, $+45^0$	67.41
3	90^0, 0^0, 90^0,	78.72
4	$\mathbf{0^0}$	**58.04**

Researchers are also studying the interaction between the outer layers of aircraft wings and internal support structures like spars, ribs, or stiffeners. This helps design wings that can better withstand deformation. For example, researchers optimize the main parts of an aircraft wing by looking at how the outer layer and ribs handle crushing loads. They use a two-level optimization approach to separate the optimization into the overall wing structure and the internal ribs. The method uses principal component analysis (PCA) and Lagrange multipliers to improve efficiency and calculate how the outer layer and ribs are connected. This approach saves computational time and improves accuracy using the PCA-based reduction scheme (Nasab *et al.,* 2020) [17].

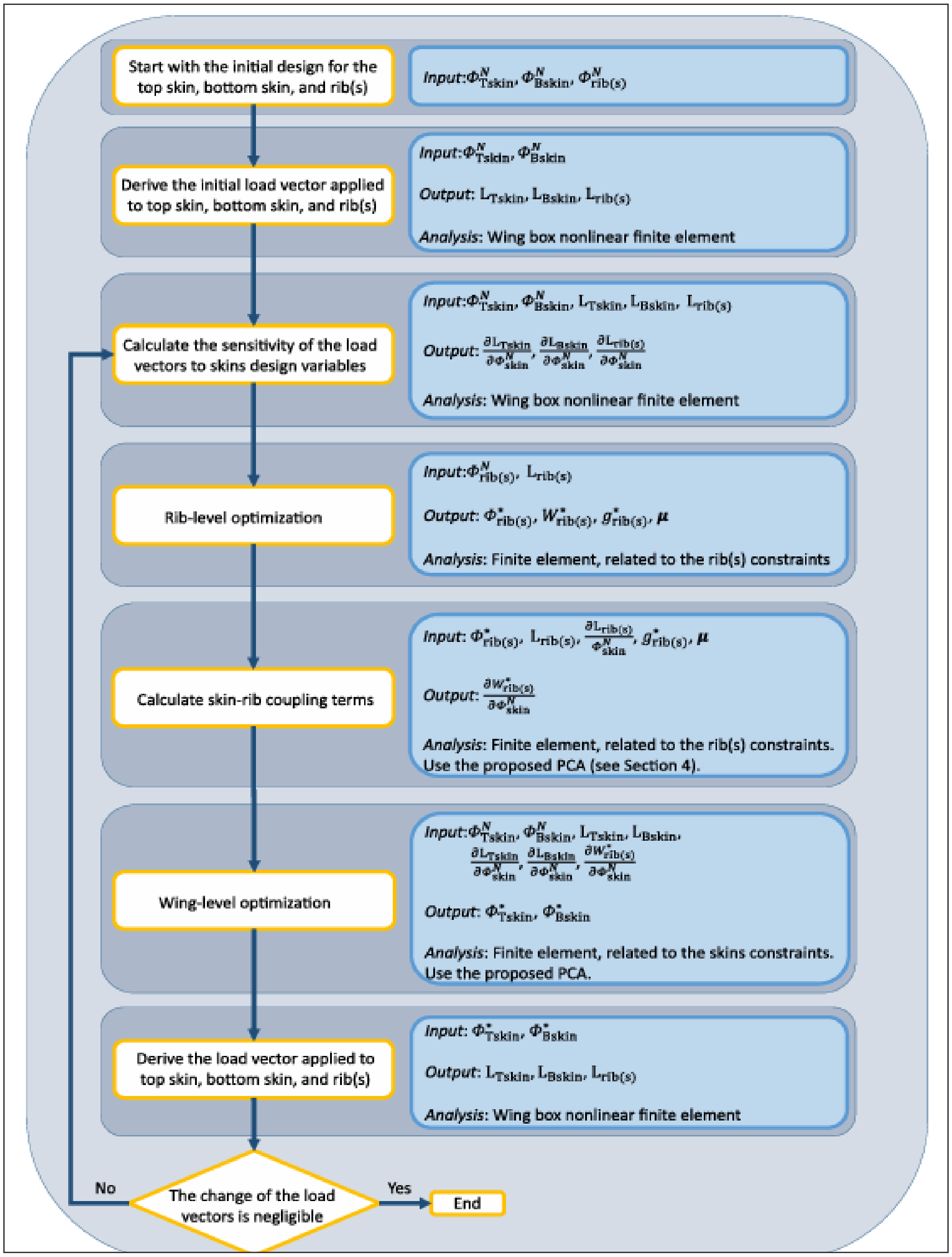

Fig. 8: Flowchart of Two-Level Skin-Rib Optimization Method (Nasab *et al.,* 2020) [17]

Zheng Hu and O. Vambol are working on optimizing composite wing ribs using topology optimization methods to improve stiffness and reduce deformations. They are employing the SIMP method and sensitivity filtering technique to enhance the wing rib structure with different fibre orientations. The results show that streamlined structures can reduce deformations by more than 20% compared to un-optimized structures (Hu and Vambol, 2020) [6]. Topology optimization is an iterative process. Fig. 9 shows the flowchart of the process.

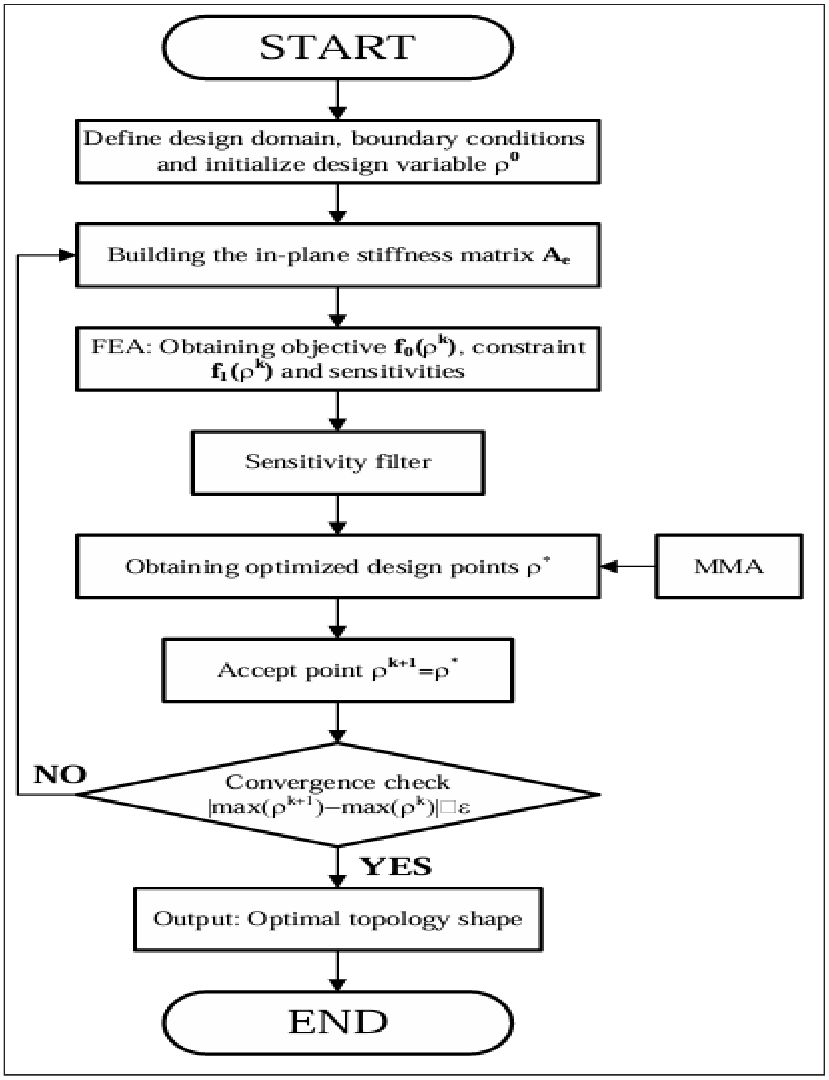

Fig. 9: Solution Flowchart of Topology Optimization (Nasab *et al.,* 2020)

Another fundamental consideration is developing cost-effective and lightweight composite wings. When we optimize designs, we not only improve performance we also take into consideration the cost and weight of the wing. Sinchai Chinvorarat utilizes Ansys Composite PrePost and Ansys mechanical module for finite element modelling to identify an optimal ply pattern that balances weight and cost while ensuring structural integrity under maximum loads. The BII2 design achieves a wing weight of 45.46 kg and a manufacturing cost of 1,288 USD. Experimental tests confirm the wing's ability to withstand specified loads without structural failure, demonstrating the effectiveness of the optimization process and the reliability of the finite element model within an acceptable error margin (Chinvorarat, 2021) [18].

Spyridon Kilimtzidis compares the equivalent plate model with a 3D finite element model, showing excellent accordance with each other and the framework minimises wing mass while maintaining its integrity (Kilimtzidis *et al*., 2023) [4]. The study demonstrates the accuracy and efficiency of EPM, making it a robust tool for the early design stages of composite aircraft wings.

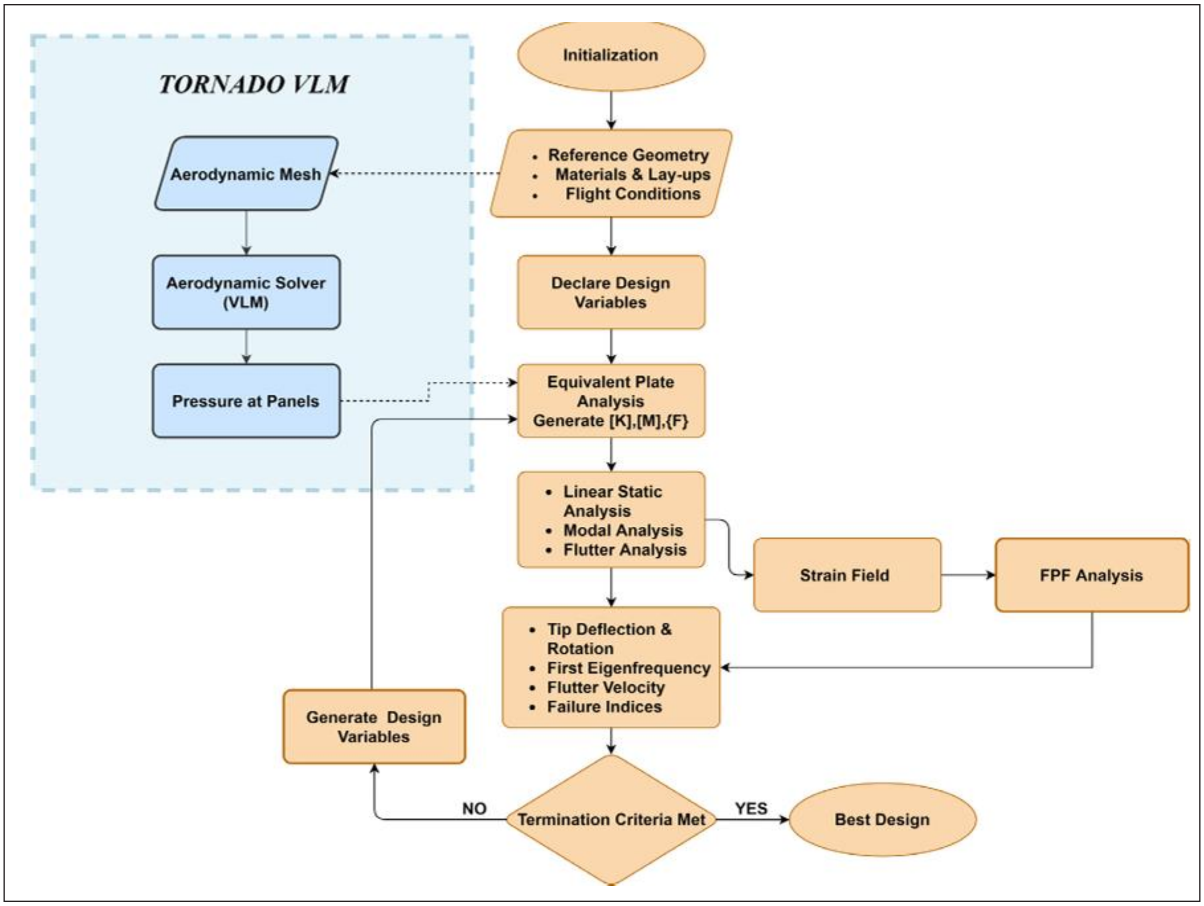

Fig. 10: EPM Optimization Flowchart (Kilimtzidis *et al.,* 2023) [4]

E. Damage Tolerance and Failure Analysis

In addition, to static stress analysis, researchers have also investigated the damage tolerance and fatigue behaviour of composite wing structures with cut-outs. Finite element-based methods have been used to identify critical locations for fatigue crack initiation and estimation of stress intensity factor for various crack lengths using the Modified Virtual Crack Closure integral (MVCCI) method (Pukale and Amarnadha Reddy, 2014; Sukeerth and Thammaiah, 2014) [19, 20]. Damage tolerance design is an effective philosophy that leads to weight reduction of aircraft structures while maintaining safety. Fig. 11 shows the variation of SIF and crack length.

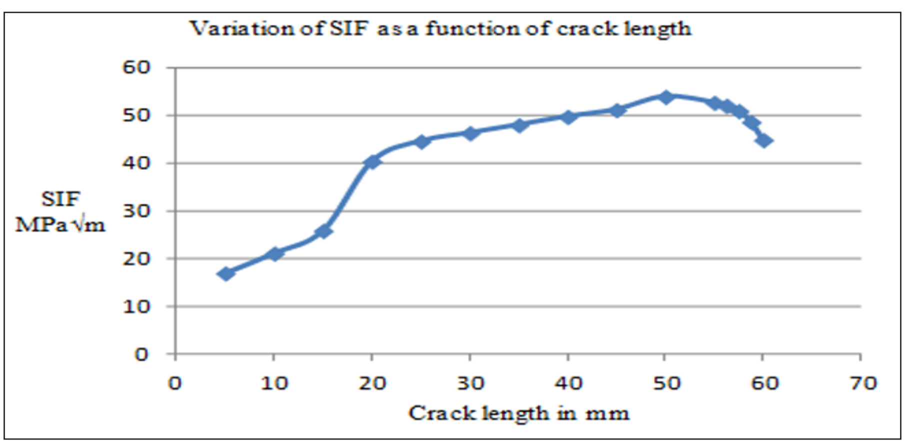

Fig. 11: Variation of SIF as a Function of Crack Length

V. Sivakumar and Bharath Kumar conducted a study on a Boeing-747 rib section with a circular cut-out under in-plane shear loading. They utilized a finite element technique in ABAQUS software to determine the stress intensity factor (SIF) along a semi-elliptical crack. The study revealed that crack dimensions and location significantly affect crack initiation, leading to variations in failure modes such as opening, sliding, and tearing (Sivakumar *et al.,* 2016) [11]. The calculated SIF values, when compared to the material's fracture toughness, suggest a higher likelihood of crack initiation, particularly at the crack edges under the specified load.

III. Conclusion and Future Perspectives

In conclusion, the review paper provides a comprehensive overview of the research on stress analysis and optimization techniques for composite aircraft structures with cut-outs. The studies reviewed highlight the importance of weight reduction in composite structures for aircraft to make economic sense and the need for efficient design procedures and advanced manufacturing techniques. The paper discusses various methods such as analytical, numerical, and experimental approaches used for stress analysis and optimization, by using Finite Element Method (FEM), optimization techniques, fibre steering, and topology optimization. The implications of these techniques are also examined for their impact on the safety, effectiveness, and performance of modern aircraft. Overall, this review paper sheds light on the dynamic field of aerospace engineering, combining advanced mathematical modelling, innovative material science, and practical deliberations for aircraft design.

Going forward, the future research in this area could focus on the following:

- Developing integrated design optimization frameworks that can simultaneously consider multiple design parameters, including cut-outs configuration, composite laminate, and other structural elements, to achieve optimal wing rib performance.
- Limited discussion on the impact of environmental factors on polylactic acid (PLA) wing rib on it performance.
- Limited discussions on the influence of varying parameters on crack initiations.
- Lacks detailed fatigue analysis on varying crack shape and length.
- Lack of comparison with other stress alleviation techniques in composites wing structure.
- Lack of research on stress concentration factors at extreme temperatures.
- Conducting extensive experimental investigations, including full-scale wing rib testing, to validate the analytical and numerical findings and provide a deeper understanding of the structural behaviour.
- Developing more comprehensive analytical models that can accurately capture the complex interactions between multiple cut-outs and the composite laminates in wing structures under loading conditions.

By addressing these research directions, the design and engineering of composite wing structures with improved structural integrity and resilience can be significantly advanced, contributing to the overall enhancement of aircraft wing design and performance.

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