Aircraft Structural Assessments in Data-limited Environments: a Validated fe Method

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Abstract — **Aircraft operators often modify aircraft configurations, install new equipment, and alter airframes to accommodate this equipment, leading to operations in flight envelopes different from original design profile. These modifications necessitate airframe structural assessments, which typically require comprehensive aircraft design data, often unavailable to operators. This study aims to develop and validate a practical method for finite element analysis (FEA) of aircraft structures in the absence of this detailed design data. Focusing on a case study involving structural analysis of an aircraft wing, this study presents assumptions and idealizations used to develop 2.5D finite element (FE) model of the wing. Fidelity of this model is established by comparing FE analysis results with experimental data. Key validation metrics include reaction forces, load distribution at wing-fuselage attachments, and deformation at reference points on the wing under design load. Comparison between FE analysis and experimental results is carried out to substantiates accuracy of these geometric simplifications and idealizations of load-carrying behaviour of structural members. Therefore, practicality of these idealizations in absence of design data is demonstrated. This study offers a novel approach for structural assessments of aircraft without relying on proprietary design data. The validated method enhances capability of aircraft operators to perform effective structural analyses, thereby extending service life of aircraft with continued airworthiness.**

Keywords: **Finite element analysis, Structural integrity, Reduced scale model, Structural idealization, Experimental validation**

Resumen — **Los operadores de aeronaves a menudo modifican las configuraciones de las aeronaves, instalan nuevos equipos y modifican las estructuras de los aviones para acomodar estos equipos, lo que lleva a operaciones en envolventes de vuelo diferentes al perfil de diseño original. Estas modificaciones requieren evaluaciones estructurales de la estructura del avión, que normalmente requieren datos completos de diseño de la aeronave, que a menudo no están disponibles para los operadores. Este estudio tiene como objetivo desarrollar y validar un método práctico para el análisis de elementos finitos (FEA) de estructuras de aeronaves en ausencia de estos datos de diseño detallados. Centrándose en un estudio de caso que involucra el análisis estructural del ala de un avión, este estudio presenta suposiciones e idealizaciones utilizadas para desarrollar un modelo de elementos finitos (FE) 2.5D del ala. La fidelidad de este modelo se establece comparando los resultados del análisis FE con datos experimentales. Las métricas clave de validación incluyen fuerzas de reacción, distribución de carga en las uniones ala-fuselaje y deformación en puntos de referencia en el ala bajo carga de diseño. Se lleva a cabo una comparación entre el análisis EF y los resultados experimentales para corroborar la precisión de estas simplificaciones geométricas e idealizaciones del comportamiento de carga de los miembros estructurales. Por lo tanto, se demuestra la practicidad de estas idealizaciones en ausencia de datos de diseño. Este estudio ofrece un enfoque novedoso para evaluaciones estructurales de aeronaves sin depender de datos de diseño patentados. El método validado mejora la capacidad de los operadores de aeronaves para realizar análisis estructurales efectivos, extendiendo así la vida útil de las aeronaves con aeronavegabilidad continua.**

Palabras clave: **Análisis de elementos finitos, integridad estructural, modelo a escala reducida, idealización estructural, validación experimental.**

I. INTRODUCTION

A. Research Problem

STRUCTURAL integrity analysis is paramount for safety, maintenance, and operational readiness of aircraft [1]. Structural integrity of aircraft is essential to prevent catastrophic failures that could lead to loss of life and equipment [2]. Moreover, structural integrity directly influences the frequency and cost of maintenance operations, as well as overall readiness of aircraft for their intended missions [3].

One of most significant hurdles in maintaining and assessing structural integrity of aging aircraft is the lack of access to comprehensive design data. This issue is exacerbated when either original equipment manufacturer (OEM) is no longer in business or has shifted focus to newer products [4]. For aircraft procured from foreign countries, the situation is often worse, with operators finding it virtually impossible to obtain necessary design data when technology transfer restrictions are in place [5].

The need for structural assessments arises from modifications made by operators to accommodate new equipment or to meet changing mission profiles [6]. These modifications can alter flight envelope and resultant structural loads, necessitating detailed analysis to ensure continued airworthiness [7]. However, unavailability of design data including CAD models, finite element (FE) models, material properties, and external loads, poses a significant challenge [8].

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Therefore, operators often rely on CAD models as templates for creating FE models [9]. This process is labour-intensive, requiring extensive geometric cleaning and discretization to produce a model suitable for analysis. FE model must be detailed enough to allow for comparison with actual deformation results, while coarse enough to ensure a quick turnaround of numerical results [10].

Moreover, as mission profiles often deviate from design profiles, and aircraft capabilities remain under-utilized or over-exploited [11]. This situation is further complicated when OEMs withdraw customer support at the end of contractual agreements, focusing instead on newer products [12]. Operators may also be forced to keep aircraft operational beyond design life due to procurement restrictions. Consequently, most operators of aging aircraft lack technical support from OEMs, making it challenging to keep them airworthy beyond design service life [13]. Therefore, to ensure the continued airworthiness of aging aircraft, structural assessments must be conducted [14]. These assessments require access to comprehensive design data, which directly impacts fidelity of the analysis. Access to accurate and detailed design data is crucial for developing reliable FE models, conducting thorough structural assessments, and ultimately ensuring safety of the aircraft [15].

B. Research Hypothesis

In the absence of detailed aircraft design data, it is hypothesized that a reduced-scale finite element model developed using appropriate material properties, structural idealizations, and computationally inexpensive finite element assumptions, can accurately represent structural behaviour of the aircraft.

C. Research Objectives

The objective of this research is to establish validity of these finite element (FE) idealizations invoked for analysis of an aircraft wing. These idealizations are intended to be highly practical, particularly when detailed aircraft design data is unavailable. This study presents a practical method for finite element analysis (FEA) of aircraft in absence of design data with reduced computational costs.

D. Section wise Organization of Document

In this research, FE model of a wing isolated from the fuselage is presented. This model is developed using idealizations proposed in this paper. The structural behaviour of FE model is validated through comparison with experimental data. A positive correlation between FE results and experimental data validates the proposed assumptions. Significance of these assumptions lays in correct structural behaviour predicted by underlying FE model.

II. LITERATURE REVIEW

A. Existing Relevant Literature

An aircraft wing is a semi-monocoque structure designed to resist and transmit aerodynamic forces to the airframe [16]. The wing is statically indeterminate due to redundant structural members. Therefore, resulting structural response of each member depend on the stiffness of adjacent members [17].

Outer skin of the wing encloses three different types of structural members [18]. Beam-type structural members running along the wing span are called spars. Longitudinal structural members, which are considerably thinner compared to spars, are referred to as stringers. The third type of structural member, called ribs, is positioned along transverse chord direction [19]. Transverse ribs and longitudinal stringers are made from stamped sheet metal, while spars are machined. These structural members work together to support external aerodynamic and inertial loads and transfer them to the airframe [20].

The skin transmits aerodynamic forces to both longitudinal members (spars and stringers) and transverse members (ribs) through plate and membrane action [21]. Along with longitudinal members, the skin reacts to applied bending and axial loads. In conjunction with transverse ribs, the skin reacts to hoop or circumferential loads due to internal pressurization. The skin also develops shear stress that reacts to applied torsional moments [22].

Longitudinal members, including spars and stringers, primarily resist bending and axial loads. They segment the skin into smaller patches, which increases the buckling and compressive failure stresses. They also help arrest crack growth in the skin [23].

Transverse ribs maintain cross-sectional wing shape, distribute concentrated loads and redistribute stresses around structural discontinuities [24]. Ribs also establish column length for longitudinal members by providing end restraint, thereby increasing buckling strength of these members.

B. Gaps in Existing Knowledge

Behaviour of wing and its structural members have been explained in detail in existing literature. However, no general guideline is available to FE analyst for developing wing models for structural analysis [25]. Therefore, FE analyst tends to use a variety of techniques ranging from simple beam model to full scale 3D model with all installed components. Fidelity and computational cost, thus, vary enormously between these extremes [26].

C. Justification for New Research

In absence of comprehensive aircraft design data, a reduced-scale finite element (FE) model is required that can deliver high-fidelity results with quick turnaround time [27]. A reduced-scale FE model is a simplified version of full-scale finite element model, based on idealization of structural members. This model is designed to accurately capture aircraft's structural performance while reducing complexity. This approach facilitates timely decision-making and ensures that structural assessments are both accurate and efficient.

III. METHODOLOGY

Idealization of load-bearing behaviour of an aircraft wing is presented for developing a reduced-scale finite element (FE) model [28]. It involves simplifying geometry, using shell and beam elements for thin-walled structures, applying averaged material properties and focusing on representative load cases. MSC Patran® and Nastran® are used for FE analysis of wing model [29]. Validation of reduced-scale FE model against available experimental data or benchmark case is carried out to substantiate accuracy of these idealizations.

IV. FE ANALYSIS OF WING

A. Idealization of Wing

The wing of an aircraft is attached to fuselage at four different locations through spars, designated as Front Wall (FW), Front Spar (FS), Main Spar (MS), and Rear Spar (RS) [30]. Only the placement and limited geometric details of these structural members are available in maintenance manuals (MM). This information is utilized to develop 2.5 D FE model. Several assumptions regarding the load-carrying capacity of the wing's structural members have been made [31]:

1. Longitudinal stiffeners and spar flanges carry only axial stresses.
2. Rib web, skin, and spar web carry only shear stresses.
3. Axial stress is assumed to be constant along cross-section of each longitudinal stiffener (spars and stringers).
4. Shear stress is assumed to be uniform throughout the web of ribs and spars.
5. Transverse frames (ribs) are considered rigid within their own planes and have no rigidity normal to their planes.

The structural members of wing have geometric details, including lightening holes [32], variations in thickness, cross-sectional warp, and manufacturing artifacts like fillets, chamfers, and radii. These features are not included in the reduced-scale FE model. Following geometric simplifications have also been carried out:

1. Using average thickness for structural members.
2. Assuming no warp in the cross-sectional shape.
3. Omitting fasteners such as bolts and rivets, with load transfer between adjoining members ensured through coincident nodes [33].

Various components installed inside the wing, such as fuel transfer valves, hydraulic actuators, landing gear attachments, and electrical ancillaries contribute to 30 % mass and internal volume of the aircraft wing [34]. These components do not contribute to structural stiffness of the wing. Additionally, flight control surfaces attached to the wing, including airspeed brakes, leading edge flaps (LEF), trailing edge flaps (TEF), and ailerons, are required for aeroelastic analysis. The present study deals with static structural analysis whereby these ancillary component and control surfaces do not add structural stiffness and hence, are not included in the model [35].

The purpose of this reduced-scale FE model is to calculate internal load distribution, load paths, structural deformation, and free-body loads [36]. The model uses 0D mass and spring elements, 1D beam elements, and 2D shell elements [37] arranged in 3D space to mimic the wing structure. Fig. 1 presents the illustration of wing and placement of internal members in wing.

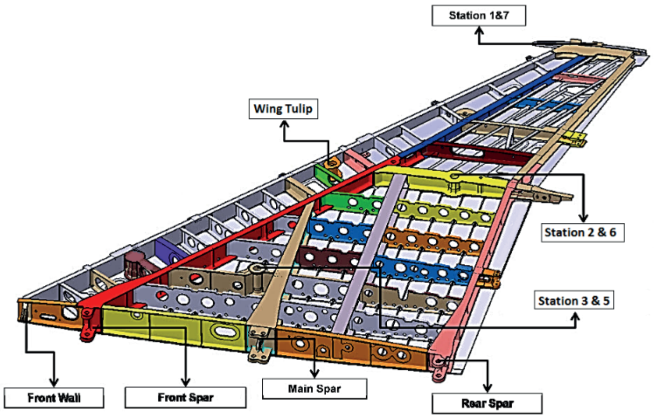

Fig. 1. Wing Model

B. Finite Elements Selection

3D solid elements are often unsuitable for modelling thin-walled aircraft structures due to the phenomenon of shear locking [38]. This issue can be mitigated by selecting first order 2D elements with appropriate mesh density (element size). Nastran Element Library recommends using shell elements (CQUAD4) and beam elements (CBEAM) for plate and beam-like structures, respectively [39]. For structures where cross-section remains constant along the length, lower-order CROD element can also be used as an alternative to beam elements.

CQUAD4 (linear 2D shell) elements is used to model aircraft skin and webs of ribs / spars. Each node in a shell element has 5 degrees of freedom (DOFs), while each node in a beam element has 6 DOFs. Flanges of ribs and spars, which carry axial loads, are modelled using beam elements. Stiffeners in skin panels and stringers in aircraft wing are modelled using 1D rod element CROD. This modelling approach balances computational efficiency with the need for accurate representation of the aircraft's structural behaviour under various loads [40]. Fig. 2 shows the finite element model of the wing with outer skin removed.

C. Material Properties

In aircraft maintenance manuals, except for nomenclature, material properties are often not provided. Due to lack of specific material details, properties available from open resources, as listed in Table 1, have been considered for the analysis.

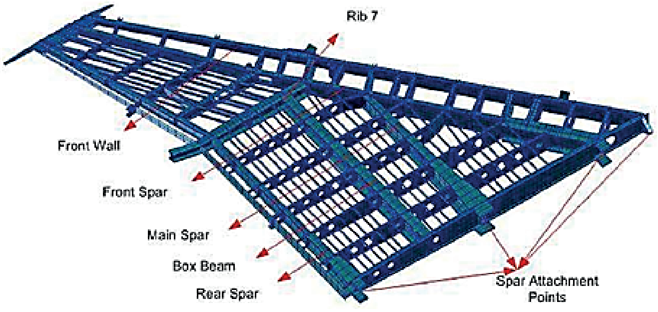

Fig. 2. Internal Members in FE Model

TABLE I
MATERIAL PROPERTIES FOR WING

Component	Material	E (GPa)	Poison Ratio(μ)
Front Wall	Al 2000 series	73.1	0.33
Front Spar			
Box Beam			
Rear Spar			
Ribs			
Stingers			
Main Spar	Steel	196	0.3
Skin	Al 7000 series	70	0.3

D. Systems of Units

MSC Patran Nastran is independent of unit system and therefore, consistency of units is the responsibility of FE analyst. For current analysis, mm, kg, s unit system is used. So, deformation output is mm and stress output is MPa.

E. Boundary Conditions

The wing is connected to a root beam which is attached to four transverse bulkheads of the fuselage. These bulkheads are modelled using beam elements (CBEAM) with a very high stiffness of 1 GN/m which are fixed at aircraft centreline (CL). Fig. 3 illustrates these boundary conditions applied on the wing.

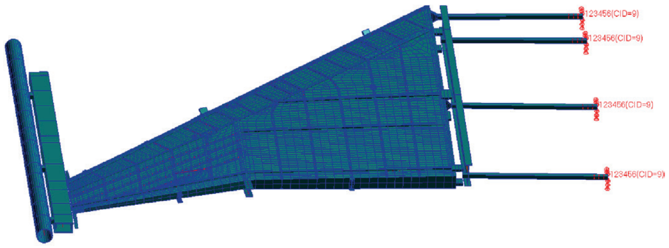

Fig. 3. Applied Boundary Conditions on Wing

Use of very stiff beam elements to represent wing-fuselage attachment offers two main benefits. [41] First, it ensures that the deflection of the wing spar attachments remains minimal, allowing the wing deformation from numerical results to closely match experimental data. Second, by applying the fixed boundary condition away from the spar attachments, it helps to avoid stress singularities at these attachment points.

F. Loads

Available experimental results were obtained by applying discrete forces to the wing through hydraulic actuators, with applied load set equal to design limit load for the wing. This load is simulated in finite element (FE) model by applying nodal forces at the locations corresponding to the actuators. Fig. 4 illustrates the application of these nodal forces on FE model of the wing.

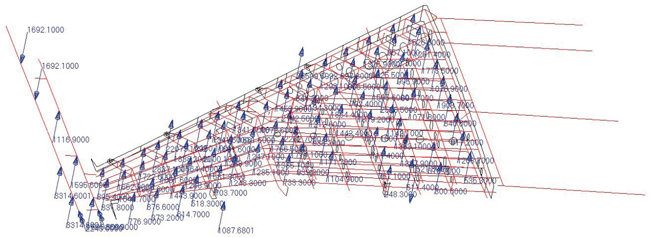

Fig. 4. Applied Load on Wing

G. Verification of FE Model

To ensure adequacy of finite element (FE) model, following steps have been implemented [42]:

1. *A mapped mesh approach is used for development of FE model of the wing.*
2. *More than 95 percent of shell elements are quadrilateral. Triangular shell elements are employed only in mesh transition regions to maintain model consistency.*
3. *Edge length for shell elements is set to 50 mm. Mesh density is adjusted to ensure at least four shell elements along beam cross-sections of ribs and spars.*
4. *Coincidence of nodes between adjoining structural members is enforced to ensure effective load transfer throughout the model.*
5. *Using default settings in MSC Patran, mesh quality checks (including taper ratio, skewness and warp) are conducted and confirm no errors.*
6. *Shell normal and beam orientations are verified to ensure consistency within FE model.*
7. *No duplicate elements or free edges are present in FE model.*

These measures collectively ensure that FE model accurately represents wing structure to produce reliable simulation results.

H. Static Structural Analysis

Finite Element analysis has been performed at design load. Pre- & Post processing is performed in MSC Patran while MSC Nastran is used as solver. Deformation field of wing under applied load is given in Fig. 5. Von-Mises equivalent stress in wing at design load is given in Fig. 6.

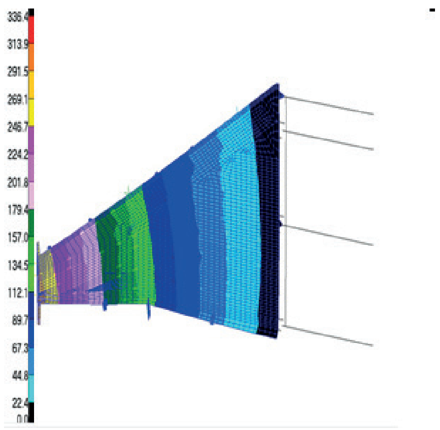

Fig. 5. Wing Deformation Field

I. Validation of FE Results

Validation of the finite element (FE) results has been performed using experimental data to substantiate the proposed assumptions and idealizations for the FE analysis of the wing. The available experimental data includes:

1. *Reactions (Forces and moments) measured at the wing attachments.*
2. *Measurements of wing deformation at various locations along the span under design load.*

By comparing these experimental data points with the results obtained from FE analysis, accuracy and reliability of underlying assumptions and idealizations of the model are assessed.

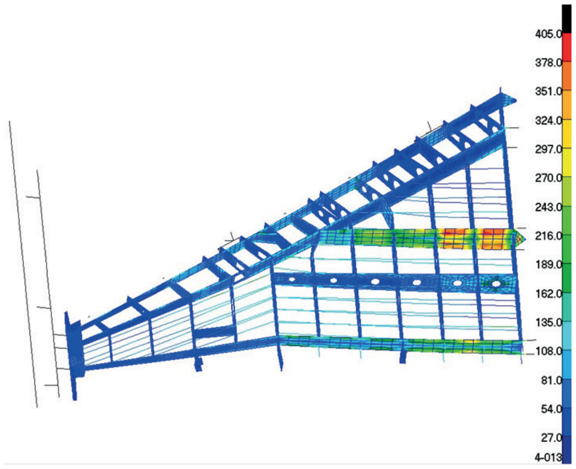

Fig. 6. Wing Stress Field (Outer Skin Removed)

V. DISCUSSION

A. Interpretation of Results

Table 2 presents comparison of reaction (forces and moments) at wing attachment for FE and experimental results. Both experimental and FE results corelate because maximum percentage difference between these results is less than 6 %.

TABLE II
COMPARISON OF REACTION FORCES

Attachment	FE Results		Experimental Results		%Age Difference	
	Force (N)	Moment (N.m)	Force (N)	Moment (N.m)	Force	Moment
Main Spar	79354	124704	83520	129950	4.99	4.04
Front Spar	37578	58431	39810	61120	5.61	4.4
Rear Spar	33643	52334	35350	54870	4.83	4.62
Front Wall	2791	4263	2915	4435	4.25	3.88
Total	153366	239732	161595	250375	--	--

Table 3 gives load distribution among wing spars from FE and experimental results. Both methods predict that main spar takes 52 % load, front spar takes 24 % load, rear spar takes 22 % and front wall takes 2 % load, approximately.

Comparison of deflection field of wing for FE and experimental results have been carried out. Front wall, front spar and rear spar run from wing root to wing tip. Fig. 7 shows the monitor points for which experimental deformation of wing under design load is available.

TABLE III
LOAD DISTRIBUTION

Attachment	FE Results		Experimental Results	
	Force %	Moment %	Force %	Moment %
Main Spar	51.74	52.02	51.68	51.9
Front Spar	24.5	24.37	24.64	24.41
Rear Spar	21.94	21.83	21.88	21.92
Front Wall	1.82	1.78	1.8	1.77
Total	100	100	100	100

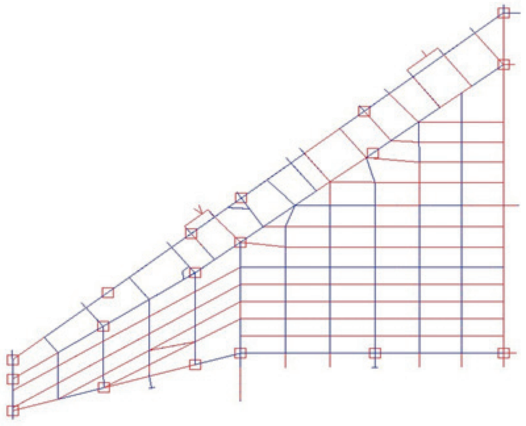

Fig. 7. Monitor Points on Wing

Fig. 8 shows the comparison of deformation of along Front Wall, Front Spar and rear spar for FE analysis and experimental results. Deformation field of wing available from both studies corelate with each other.

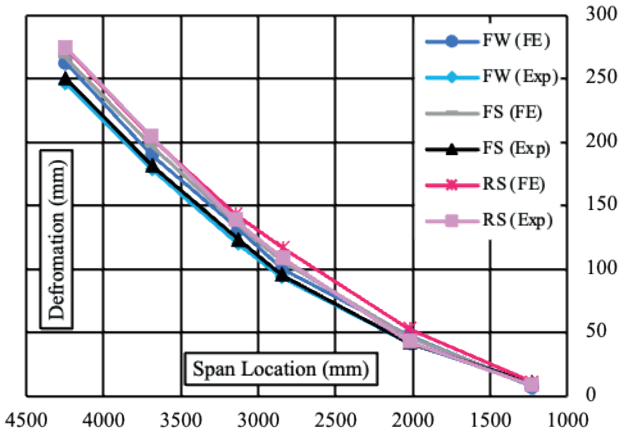

Fig. 8. Comparison of Deformation along Wing Spars

B. Research Questions and Hypothesis

Validation of FE results confirms that the idealized behaviour of wing structure can be accurately assumed. It has been demonstrated that geometric simplifications do not significantly impact the deformation field of the aircraft structure. Additionally, it has been validated that the fasteners can be excluded from FE model, with load transfer effectively facilitated through coincident nodes. Effects of surface and heat treatments on the mechanical behaviour of structural members can be disregarded in FE model without compromising accuracy. Use of candidate material properties, rather than exact material specifications, is acceptable for modelling structural members in FE model. These findings provide comprehensive answers to key research questions, substantiating the initial hypothesis that such assumptions are valid for aircraft structural analysis. The study demonstrates that idealized behaviour and simplifications can be reliably used in FE modelling without adversely affecting accuracy of results.

C. Placement of Results with Existing Literature

These findings are unique within existing literature, addressing the limitations of both low-fidelity analysis and computationally expensive methods. It has been demonstrated that useful and accurate results can be achieved by implementing these idealizations and assumptions with minimal computational cost. This approach provides a practical solution for analyzing aircraft structures, especially when detailed design data is unavailable.

VI. CONCLUSION AND RECOMMENDATIONS

Comparison of reaction forces, load distribution, and deformation field of the wing with experimental results validates the methodology for development of FE model. This validation confirms that the following idealizations are useful for FE analysis:

1. *Idealized behaviour of structural members in the wing can be assumed for static structural analysis. Longitudinal stiffeners and spar flanges carry only axial stresses. Rib web, skin, and spar web carry only shear stresses.*
2. *Geometric simplifications can be made in FE model, omitting manufacturing features like fillets, chamfers, and small cut-outs.*
3. *In absence of specific material nomenclature, reasonable material properties can be used for components, and effect of surface treatments on mechanical behaviour of structural members can be ignored.*
4. *Fasteners can be excluded from FE model, with load transfer effectively handled through coincident nodes.*
5. *Far-field boundary conditions can be applied to isolate structural members from the global assembly. This boundary condition can provide an accurate approximation of their structural behaviour.*

These validated assumptions streamline modelling process and ensure accuracy of FE model without requiring exhaustive detail, thus facilitating efficient and reliable structural analysis.

A. Contributions of Present Research

This research offers a methodology for developing a reduced-scale FE model of aircraft structures. The reduced-scale model can be developed using information accessible to aircraft operators, without relying on detailed design data. This model is particularly advantageous for achieving a quick turnaround of results during design iterations and modification phases. This approach enables effective structural analysis and decision-making, even the absence of proprietary design details, thereby supporting maintenance and modification efforts.

B. Benefits and Limitations of Proposed Solution

The proposed solution offers accurate predictions of deformation and load transfer paths within the aircraft wing. Extension of this methodology for the development of FE model of aircraft fuselage is also required to establish its robustness. Further studies are also necessary to verify the stress results obtained from the reduced-scale finite element model. These additional investigations will help ensure the reliability and accuracy of stress distributions, providing a more comprehensive validation of the methodology.

C. Potential Applications

This research holds significant potential in the field of aerospace engineering. By employing proposed idealizations, a reduced-scale finite element model can be developed, which effectively captures the structural behaviour of the aircraft. In absence of design data, this model offers high-fidelity results at minimal computational cost, making it a valuable tool for structural analysis, design optimization, and modifications in aerospace applications.

D. Future Lines of Research

It is recommended that a strain gauge survey of the complete wing under design load be conducted to verify the fidelity of 2.5D FE model for stress calculation. This experimental validation would ensure that the model accurately represents the stress distributions within the wing structure, providing a more comprehensive assessment of its reliability and accuracy.

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