



Load Optimization Method for Fatigue Testing of Large Deformation Structures Based on Stiffness Matching

Fahad Abul Kalam*

School of Aeronautics, Northwestern Polytechnical University, Xi'an 710021, China



Abstract

To enhance the efficiency and accuracy of load optimization for fatigue testing of large deformation structures, this paper introduces a novel load optimization method grounded in stiffness matching. The core of this approach is the utilization of displacement response error as the primary optimization objective. It establishes a robust closed-loop framework: "Test State Load Optimization Design Stiffness Model-Based Displacement Response Calculation Displacement Response Error Evaluation." This comprehensive framework is designed to ensure the precise assessment of structural stiffness and to guarantee that critical displacement responses meet stringent requirements. Initially, simplified linear and non-linear finite element stiffness models of the structure are meticulously constructed and identified using historical test data. Subsequently, a sophisticated load reconstruction model for large deformation structures is developed. This model integrates theoretical loads into the deflection curve to accurately determine loading point coordinates and force directions, which are crucial for realistic simulation. The efficacy of this method is demonstrated through a case study involving a high-aspect-ratio wing. The results unequivocally show that this method effectively accounts for the complex effects of structural deformation, optimizes both loading coordinates and applied loads, and achieves a remarkable consistency between experimental and theoretical structural responses. This leads to a significant improvement in both precision and efficiency, substantially outperforming conventional load optimization techniques.

Keywords: Large Deformation Structures; Load Optimization; Stiffness Matching; Model Reconstruction; Geometric Non-linearity; Fatigue Testing

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*Correspondence:

Fahad Abul Kalam, School of Aeronautics, Northwestern Polytechnical University, Xi'an 710021, China; Tel: 01920475676;

E-mail: mambub42@gmail.com

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Introduction

Full-scale fatigue testing is a cornerstone in the aerospace industry, indispensable for validating the fatigue and durability performance of aircraft structures subjected to repetitive loading cycles. These tests meticulously simulate the diverse load conditions encountered during an aircraft's operational life, with primary objectives including the identification of fatigue-prone areas, determination of the aircraft's structural service life, and the formulation of comprehensive maintenance and inspection schedules [1-5]. The execution of full-scale fatigue tests necessitate a sophisticated loading facility capable of applying all specified load conditions by effectively distributing equivalent loads across a set of designated test loading points. The inherent complexity of this process makes error control in fatigue test load optimization particularly challenging, as inaccuracies directly impact the precision of structural assessment.

Traditionally, load optimization procedures have been predicated on the jig configuration (0G configuration), which inherently neglects the changes in aircraft configuration induced by significant structural deformations. While this simplification is often permissible for structures exhibiting minor deformations, its impact becomes increasingly pronounced and problematic as structural dimensions and flexibility escalate, particularly in modern aircraft designs featuring high-aspect-ratio wings [6, 7]. In such scenarios, the conventional approach leads to substantial discrepancies between the simulated and actual load distributions, compromising the validity of the test results.

Prior research has explored various techniques for error control and pre-loading in the context of high-aspect-ratio wings [8-11]. However, these methods frequently suffer from limitations, such as the absence of explicit load correction methodologies or the inability to provide real-time comparisons between theoretical and experimental displacement responses during the iterative optimization process. The continuous advancement in wide-body aircraft development further exacerbates the challenges associated with accurately simulating large loads and accommodating large deformations [12-14]. This paper addresses these critical gaps by introducing a novel

methodology that not only prioritizes accurate stiffness assessment but also ensures a high degree of displacement consistency between the test and theoretical states throughout the load optimization process.

Research on Stiffness Matching Methods

The accurate assessment of structural behavior under fatigue loading, especially for large deformation structures, necessitates robust modeling techniques. Traditional error assessment methods often rely heavily on complex, high-fidelity finite element models (FEM). While powerful, the development and calibration of these models with experimental data are notoriously time-consuming and resource-intensive [15-16]. Furthermore, for structures undergoing large deformations, the consideration of geometric non-linearity becomes paramount. Neglecting this aspect can lead to significant inaccuracies, as the structural response is no longer linearly proportional to the applied loads. Repeated iterative calculations, which are often required in non-linear analysis, can render full-scale FEM computationally prohibitive during the load optimization process. To circumvent these computational bottlenecks, the development of a simplified stiffness model offers a substantial improvement in efficiency, enabling real-time non-linear analysis and comparison of structural responses during load optimization.

A. Linear Stiffness Calculation

For initial analysis and as a foundation for non-linear models, the wing structure can be effectively simplified into a cantilever beam model, composed of plane beam elements and rod elements. The element stiffness matrix, K_e , for such a system is derived from fundamental principles of structural mechanics:

$$K_e = E \int_0^L \int_A B^T B dA dx \quad \text{Eq 1}$$

where E represents Young's modulus, L is the length of the element, A is the cross-sectional area, and B is the strain-displacement matrix. The global stiffness matrix K and the corresponding global load vector f are then systematically assembled using the direct stiffness method (superposition method) from the individual element stiffness matrices. This assembly process culminates in the global equilibrium equation:

$$K\delta = f \quad \text{Eq 2}$$

Here, δ represents the global displacement vector, encompassing the displacements and rotations at each node of the discretized structure. This linear formulation provides a foundational understanding of the structure's elastic behavior under small deformations.

B. Non-linear Stiffness Calculation and Geometric Non-linearity

When structures undergo large deformations, the fundamental assumption of linear elasticity, where equilibrium equations are formulated based on the undeformed configuration, becomes invalid. In such cases, the equilibrium equations must be established in the deformed state to accurately capture the structural response. This paper employs the Updated Lagrangian (UL) method for geometric non-linear analysis. The UL formulation considers the equilibrium of the structure in its current (deformed) configuration, updating the geometry at each incremental step of loading. A critical component in non-linear analysis is the tangent stiffness matrix, K_t , which accounts for the changing stiffness characteristics of the structure as it deforms.

The tangent stiffness matrix is composed of two primary parts:

$$K_t = K_E + K_G \quad \text{Eq 3}$$

where K_E is the elastic stiffness matrix (similar to the linear stiffness matrix but evaluated at the current configuration), and K_G is the geometric stiffness matrix. The geometric stiffness matrix captures the influence of existing stresses (internal forces) on the overall stiffness of the structure, particularly the stiffening or softening effects due to large displacements and rotations. This is crucial for accurately modeling phenomena such as tension stiffening or buckling behavior. The non-linear system of equations is typically solved using an incremental-iterative method, such as the Newton-Raphson iteration. This method involves breaking down the total load into a series of incremental steps and iteratively solving for the displacement increments within each step. The iterative process continues until the residual force, R_i , which represents the imbalance between internal and external forces, converges within a specified tolerance ϵ [17]. This ensures that the calculated displacements accurately reflect the non-linear behavior of the structure.

C. Model Stiffness Identification

The process of model stiffness identification is crucial for developing accurate and reliable simplified structural models. This involves determining the structural parameters that govern the load-displacement relationship based on available data. The load-displacement data can be sourced from various origins, including:

- 1) **Historical experimental data:** Actual measurements from previously conducted tests provide invaluable insights into the real-world behavior of the structure.
- 2) **Data extracted from high-fidelity FEM:** Results from detailed finite element models can be used to generate synthetic load-displacement data, especially when experimental data is scarce or expensive to obtain.
- 3) **Pre-test loading data:** Data collected during preliminary loading phases of a test can be used for real-time model calibration.

For stiffness identification, it is essential to select load-displacement data within the elastic range of the structure to ensure that the identified stiffness parameters are representative of its elastic properties. An optimization model is then constructed where the design variables are typically the section modulus coefficients (e.g., x_i) for each beam element. These coefficients are used to modify the nominal section properties, such as the moment of inertia (I_{0xi}). The objective of this optimization is to minimize the error between the displacement responses calculated by the established finite element stiffness model and the actual measured displacement data. A non-linear least squares method is commonly employed for this purpose, iteratively adjusting the section inertia coefficients until the discrepancy is minimized. Furthermore, to ensure a physically realistic and continuous stiffness distribution, particularly for complex structures like wing spars, any localized singularities in the bending stiffness distribution are corrected based on established structural design principles [18].

Fatigue Test Load Calculation for Large Deformation

In the context of full-scale fatigue testing, the application of cyclic loads to an aircraft structure in a laboratory setting aims to faithfully replicate the load history experienced during actual flight operations.

This is achieved by strategically positioning a number of loading points on the structure, through which loads corresponding to various flight conditions are applied. Typically, each loading point is approximated as a two-pin joint mechanism, comprising a hydraulic actuator and sensors. One pin joint (hinge point 1) is rigidly connected to the test specimen, while the other (hinge point 2) is fixed to the ground or a specialized load-bearing apparatus. The location of hinge points 1 defines the loading point coordinates, and the line connecting hinge point 1 (movable segment) and hinge point 2 (fixed end) dictates the direction of the applied force line, as illustrated in Figure 1 of the original document.

As loads are applied and the structure deforms, the position of hinge point 1 continuously changes, leading to dynamic alterations in both the loading point coordinates and the force line direction. For structures undergoing small deformations, these changes can often be neglected without significantly impacting the accuracy of the applied loads. However, for large deformation structures, such as high-aspect-ratio wings, ignoring these dynamic changes can introduce substantial errors in the fatigue test load optimization process. Therefore, in the fatigue test load optimization of large deformation structures, it is imperative to explicitly account for the influence of structural deformation on load application under different operating conditions.

This phenomenon, often referred to as the follower force effect, is critical for accurate load application [12]. By substituting the theoretical loads into the established simplified stiffness model, the deformation curve for each load case can be accurately fitted. This fitted curve then allows for the precise calculation of the deformed loading point coordinates and the corresponding control section positions. These dynamically updated coordinates and positions serve as the fundamental baseline for subsequent load optimization calculations, ensuring that the applied loads accurately reflect the intended theoretical conditions on the deformed structure.

Load Optimization Process

The primary objective of the load optimization process is to minimize the displacement response errors while rigorously satisfying all specified load constraints. This involves a sophisticated iterative approach that adjusts both the magnitude and application points of the loads.

A. Loading Point Load Optimization

In this stage, the primary design variables are the load magnitudes, F_i , applied at each individual loading point. The optimization is subject to several critical constraints:

Equality Constraints: The total vertical load and the total moment exerted on the structure must precisely match their theoretical design values. This ensures that the overall loading conditions are consistent with the aircraft's operational requirements.

Inequality Constraints: The errors in shear force and bending moment at designated control sections must remain within predefined limits. For instance, the original document specifies a maximum allowable error of 3% for shear force and 2% for bending moment. These constraints are vital for maintaining the structural integrity and preventing localized overstressing.

The objective function for this optimization problem is formulated to minimize the weighted sum of the squared relative

errors in displacement responses at various measurement points:

$$\min f(F) = \sum_i w_i \left(\frac{D_{test,i} - D_{theory,i}}{D_{theory,i}} \right)^2 \quad \text{Eq 4}$$

where F represents the vector of loading point forces, w_i are the weighting coefficients assigned to each displacement measurement point (reflecting their relative importance), $D_{test,i}$ is the measured (or simulated experimental) displacement response at point i , and $D_{theory,i}$ is the corresponding theoretical displacement response. This formulation ensures that the optimization drives the experimental setup towards a displacement field that closely matches the theoretical predictions. Genetic Algorithms (GA) are often employed for this type of optimization due to their ability to efficiently search complex, multi-modal design spaces [19].

When considering large deformations, both the loading point coordinates and the force line directions undergo significant changes. Consequently, the coordinates of the control sections also shift. To accurately calculate the accumulated bending moments at these control sections, it is essential to account for the contributions from both vertical and spanwise components of the forces. The calculation formula for the bending moment M_i at a control section, considering these dynamic changes, is given by:

$$M_i = \sum (-F_i \cdot ZHFL(i, 2) \cdot dz + F_i \cdot ZHFL(i, 3) \cdot dy) \quad \text{Eq 5}$$

where $ZHFL(i, 2)$ and $ZHFL(i, 3)$ represent the load components in the vertical and spanwise directions, respectively, and dz and dy are the respective moment arms from the loading point to the control section.

B. Installation Coordinate Optimization

Beyond optimizing the load magnitudes, the precise installation coordinates of the loading points (specifically, the fixed hinge point 2) play a crucial role in minimizing load application errors, especially when structural deformation is significant. While a baseline position for hinge point 2 can be determined from a typical load state, achieving an optimal arrangement often requires further refinement. The most ideal approach involves synchronously optimizing the loading point installation coordinates alongside the load magnitudes during the optimization process. Changes in the installation position of hinge point 2 directly influence the actual force line direction for different load cases, thereby affecting the overall accuracy of the load optimization. Therefore, optimizing the installation coordinates of hinge point 2 (referred to as loading point installation coordinates) is essential.

This synchronous optimization is typically implemented using a two-layer iterative process:

1) **Outer Loop:** The design variables in this layer are the installation coordinates of all loading points. This loop explores different geometric configurations of the loading setup.

2) **Inner Loop:** For a given set of installation coordinates determined by the outer loop, this layer optimizes the load magnitudes at each loading point. It calculates the optimal loads and the corresponding control section errors based on the current installation coordinates.

This iterative process continues, refining the loading point coordinates and load magnitudes, until the error criteria are met or a maximum number of iterations is reached. The output of this process includes the optimal loading point installation coordinates, the

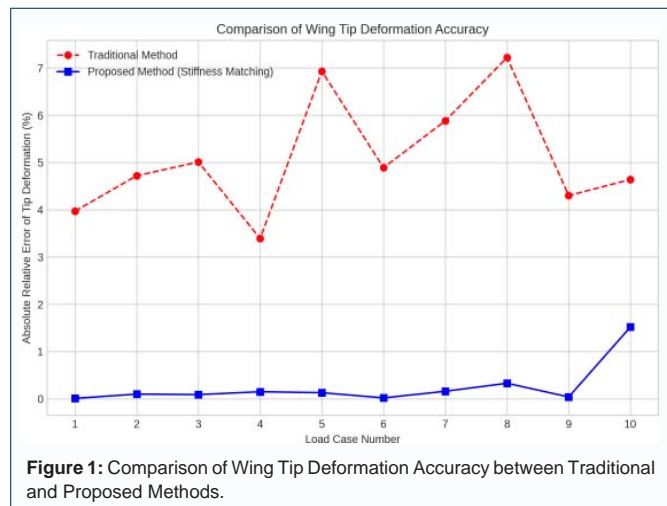


Figure 1: Comparison of Wing Tip Deformation Accuracy between Traditional and Proposed Methods.

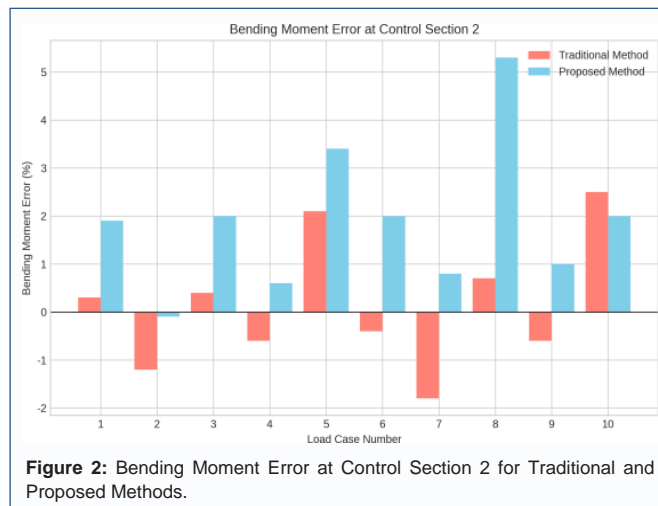


Figure 2: Bending Moment Error at Control Section 2 for Traditional and Proposed Methods.

corresponding loading point forces, and the load optimization errors for each load case under these optimized conditions. This detailed flow is conceptually depicted in Figure 2 of the original document.

Case Study and Validation

To validate the proposed stiffness matching load optimization method, a specific case study was conducted on a section of an aircraft wing. The chosen wing section was a double-beam, long, straight wing with a slender, variable-diameter hollow circular tube as its main load-bearing structure. An outer section of this wing, with a span of approximately 19 meters, was selected for fatigue test load optimization. The fatigue test involved 10 distinct load cases. Three critical control sections were established at Z=0mm, Z=6600mm, and Z=13200mm. The objective was to ensure that the bending moment error at each control section remained within 2%, and the shear force error within 3%. A significant characteristic of this wing section was its large maximum tip deformation, reaching approximately 2700mm, which underscored the necessity of considering structural deformation effects on load optimization accuracy. Furthermore, to enhance both efficiency and precision, real-time comparison of wing tip deformation was integrated into the load optimization process, ensuring consistency in the wing's deformation curve before and after optimization.

Both the traditional load optimization method and the proposed stiffness matching method were applied to this case study. The traditional method, which does not account for structural deformation during the load optimization process, required a post-hoc recalculation of actual section errors after considering the deformation. In contrast, the proposed method utilized the identified wing stiffness to synchronously optimize both the loading point installation coordinates and the load magnitudes. Following the optimization, a comprehensive error analysis was performed, encompassing control section shear force and bending moment errors, as well as a comparative analysis of wing tip deformation.

A. Comparison of Results

The following charts visually represent the significant improvements in accuracy achieved by the proposed method compared to the traditional approach.

1) **Wing Tip Deformation Accuracy:** The traditional method exhibited a substantial relative error in wing tip deformation, reaching

up to 7.22% in some load cases. This level of error is often unacceptable in critical aerospace applications. In stark contrast, the proposed stiffness matching method consistently maintained the absolute relative error in wing tip deformation below 2% for the majority of load cases, and significantly lower for many, demonstrating a marked improvement in predicting and controlling the structural response.

2) **Bending Moment Accuracy at Control Section 2:** Analysis of the bending moment errors at Control Section 2 revealed that the traditional method frequently failed to meet the stringent 2% error requirement when the effects of deformation were subsequently considered. This highlights a critical limitation of approaches that do not integrate deformation effects directly into the optimization. The proposed method, by optimizing the loads and installation coordinates with stiffness matching, effectively maintained the bending moment errors within acceptable limits, thereby ensuring greater consistency between the theoretical design and the experimental realization.

B. Summary of Data

The following table provides a detailed summary of the performance metrics for both methods across the 10 load cases, illustrating the quantitative advantages of the proposed approach:

See Table 1.

Conclusion

The proposed stiffness matching method for load optimization in large deformation structures offers several significant advantages,

Table 1: Summary of performance metrics for traditional and proposed methods.

Case	Trad. Tip Def. Error (%)	Prop. Tip Def. Error (%)	Trad. Bending Error S2 (%)	Prop. Bending Error S2 (%)
1	-3.97	0.01	0.3	1.9
2	-4.72	-0.10	-1.2	-0.1
3	-5.01	0.09	0.4	2.0
4	-3.39	-0.15	-0.6	0.6
5	-6.93	0.13	2.1	3.4
6	-4.89	0.02	-0.4	2.0
7	-5.88	-0.16	-1.8	0.8
8	-7.22	-0.33	0.7	5.3
9	-4.30	0.04	-0.6	1.0
10	-4.64	-1.52	2.5	2.0

addressing critical limitations of traditional approaches and enhancing the reliability and accuracy of fatigue testing for modern aircraft components:

1) **Enhanced Accuracy and Stiffness Assessment:** By employing a closed-loop evaluation of displacement responses, the method ensures that the structural stiffness is accurately assessed throughout the loading process. This direct feedback mechanism allows for continuous refinement and correction, leading to a more precise representation of the structure's behavior under test conditions.

2) **Improved Efficiency through Simplified Models:** The utilization of simplified non-linear stiffness models significantly boosts computational efficiency. This enables real-time iteration during the optimization process, which is crucial for handling the complexities of large deformations without incurring the prohibitive computational costs associated with full-scale, high-fidelity finite element models. This efficiency gain allows for more rapid design cycles and testing iterations.

3) **Consistency between Experimental and Theoretical States:** A key strength of this method is its ability to achieve a high degree of consistency between the experimental and theoretical structural responses. By accounting for geometric non-linearity and dynamically adjusting loading parameters, the method ensures that the fatigue test accurately replicates the intended theoretical load conditions on the deformed structure, thereby increasing the validity and reliability of the test results for flexible aircraft components.

4) **Comprehensive Optimization:** The method not only optimizes load magnitudes but also considers the dynamic changes in loading point coordinates and force line directions due to structural deformation. This comprehensive approach, including the optimization of installation coordinates, leads to a more realistic and accurate application of test loads.

In summary, the stiffness matching method represents a substantial advancement in fatigue test load optimization for large deformation structures, offering a more accurate, efficient, and consistent approach to validating the structural integrity of advanced aerospace designs.

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