

# Digital Twinning of Aerospace Structures

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HASAN HUSEYIN CAMUZ, HALIL CAGRI YILMAZ,  
ERKAN OTERKUS and SELDA OTERKUS

## ABSTRACT

Digital twinning has emerged as a cutting-edge technology with significant applications across various industries, including the aerospace sector. Aerospace components operate in harsh environments that may induce severe loads, increasing the risk of catastrophic failures and resulting in substantial human and financial implications. To mitigate these risks, a digital twin framework can be employed for structural health monitoring. Although multiple digital twinning methodologies exist, each with distinct advantages, the inverse Finite Element Method (iFEM) stands out due to its capacity for transforming discrete strain sensor readings into full-field structural response data. This comprehensive dataset—which can encompass displacements, strains, and stresses—enables the construction of an accurate digital representation of the structure. By applying relevant failure criteria to these data, potential damage can be identified at early stages, allowing for timely maintenance or corrective actions.

In this study, representative aerospace structures composed of both isotropic and composite materials will be investigated. Collected strain sensor data will be processed via the iFEM methodology to generate digital twins of these structures. Through this approach, the applicability and effectiveness of iFEM for aerospace applications will be demonstrated, highlighting its potential to enhance safety and reduce operational costs in the industry.

## INTRODUCTION

### Background

Digital twinning has emerged as a transformative technology, offering unprecedented opportunities for enhancing the safety, performance, and reliability of aerospace structures. In recent decades, aerospace components have increasingly been subjected to demanding operational conditions, including severe mechanical loads, fluctuating thermal environments, and corrosive atmospheres. Such challenging operational conditions significantly elevate the risk of structural deterioration and catastrophic failures, leading to potential human casualties and substantial economic consequences. Consequently, ensuring the structural integrity and reliability of aerospace components through effective structural health monitoring (SHM) techniques has become critically important.

Structural health monitoring systems traditionally aim to detect structural anomalies and damages at an early stage, thereby reducing maintenance costs, extending structural lifespans, and enhancing operational safety. However, conventional SHM methods, such as vibration-based modal analysis, ultrasonic inspection, and acoustic emission techniques, often require external excitation or rely extensively on detailed knowledge of the applied loads and precise material properties. Such requirements limit their real-time applicability and robustness in operational environments, thus prompting the exploration and development of alternative methods that can efficiently overcome these limitations.

Digital twin technologies offer a revolutionary solution by creating virtual representations that continuously mirror the real-time structural state of aerospace structures. Integral to successful digital twinning is the ability to accurately reconstruct the full-field structural responses from discrete, sparse sensor measurements in real-time without necessitating comprehensive prior knowledge of external loads or precise material characterization. In this context, the inverse Finite Element Method (iFEM) has attracted significant attention as a robust and practical SHM approach.

Developed initially by Tessler and Spangler at NASA Langley, iFEM reconstructs structural responses by leveraging strain data obtained from a network of strain sensors strategically positioned across the structure. Unlike conventional SHM methodologies, iFEM provides real-time, full-field reconstruction of displacements, strains, and stresses, effectively circumventing the requirement for detailed load and material information. These distinctive features significantly enhance the practicality, versatility, and real-time applicability of the iFEM methodology for aerospace SHM applications.

## **Objectives**

This study aims to comprehensively investigate the applicability, effectiveness, and robustness of the inverse Finite Element Method (iFEM) within the framework of digital twin technologies specifically tailored for aerospace structural health monitoring applications. The main objectives are:

- To implement and validate an advanced iFEM framework capable of real-time full-field response reconstruction using sparse strain measurements.
- To demonstrate the method's efficacy for aerospace structural components fabricated from both isotropic and composite materials under representative loading conditions.
- To assess the accuracy, robustness, and sensitivity of iFEM-based digital twins in detecting structural damage or anomalies.
- To evaluate the influence of sensor placement strategies on the accuracy and effectiveness of the iFEM approach.
- To highlight the practical benefits, limitations, and potential areas of improvement in deploying iFEM-based digital twins for aerospace industry applications.

## LITERATURE REVIEW

### Overview of Structural Health Monitoring (SHM)

Structural health monitoring encompasses techniques aimed at continuous or periodic assessment of structural integrity through the detection, localization, and quantification of structural damage. Traditional methods include vibration-based modal analysis, ultrasonic testing, acoustic emission, and infrared thermography. Each of these methods has specific advantages and limitations. For instance, vibration-based modal analysis is highly sensitive to structural stiffness changes, making it suitable for global damage detection; however, it often requires external excitation and detailed baseline information, limiting real-time applicability [1,2]. Ultrasonic testing is effective in detecting localized internal flaws but necessitates comprehensive structural scanning and direct access to monitored regions, restricting its practical implementation [3].

### Digital Twin Technologies in Aerospace

Digital twinning involves creating a virtual model of a physical asset that updates and evolves based on real-time data. Within aerospace, digital twins have been extensively investigated to enable predictive maintenance, optimize structural designs, and enhance operational efficiency. Glaessgen and Stargel (2012) described digital twin technology as essential for understanding structural performance and predicting life-cycle behavior, emphasizing its strategic importance for future aerospace platforms [4]. Furthermore, Tuegel et al. (2011) highlighted the critical role of digital twins in capturing real-time responses and predicting structural integrity under varying operational scenarios, thereby significantly reducing maintenance time and improving flight safety [5].

### Overview of Inverse Finite Element Method (iFEM)

The inverse Finite Element Method, initially proposed by Tessler and Spangler, reconstructs full-field structural responses such as displacement, strain, and stress from discrete strain measurements [6,7]. The iFEM methodology minimizes a weighted least-squares functional to derive nodal displacement fields without explicit knowledge of loading or material properties, a distinctive advantage over conventional FEM and SHM approaches. The method has demonstrated significant promise due to its computational efficiency, robustness, and real-time applicability, making it particularly suited for aerospace structural health monitoring [8]. Mathematically, the iFEM approach involves the minimization of the following functional:

$$\Phi(\mathbf{u}) = \sum_{e=1}^n w_e \|\epsilon^{(e)}(\mathbf{u}^{(e)}) - \epsilon_{input}^{(e)}\|^2 \quad (1)$$

Here,  $u^{(e)}$  is the nodal displacement vector for each element  $e$ ,  $\epsilon^{(e)}$  are analytical strains, and  $\epsilon_{input}^{(e)}$  represent experimentally measured strains. Minimizing this functional provides the most accurate estimate of structural behavior consistent with sensor measurements [8,9].

## Review of Previous Studies Using iFEM in Aerospace Applications

Significant advancements have been achieved using iFEM in aerospace structural applications. Kefal et al. (2016) introduced a four-node quadrilateral inverse shell element with drilling degrees of freedom, demonstrating its effectiveness for shape sensing and SHM in thin-walled aerospace structures [1]. Similarly, Li et al. (2024) developed a two-dimensional four-node quadrilateral inverse element (iQP4) specifically designed for shape sensing and structural health monitoring, validating its accuracy through comparative studies with traditional FEM analysis [9].

In another critical study, Kefal et al. (2017) enhanced the iFEM framework to monitor displacements and stresses in multilayered composite and sandwich structures. Their work illustrated the method's capacity to accurately capture structural responses even with sparse sensor configurations, further establishing the method's suitability for complex aerospace structural systems [10].

Moreover, NASA has extensively employed iFEM for shape and stress sensing applications in various aerospace platforms, demonstrating the robustness of the methodology in real-world operational environments [6,7].

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