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Fracture stress triaxiality of Ti-6Al-4V for computational design of damage tolerant aeroengines

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Abstract

Fracture stress triaxiality affects the maximum deformation of materials, and reliable computational design of damage-tolerant aircraft depends on accurate predictions of this state variable. This numerical study analyses the effect of fracture stress triaxiality on the damage behavior of Ti-6Al-4V during aero-engine fan blade-out events using explicit dynamic finite element analysis. Experimental data used in previously reported model calibration are compared with analytical predictions of the Johnson-Cook damage model and with preliminary simulation results of stress-triaxiality at fracture in the shroud due to a fan blade-out. This analysis is necessary to ensure that the structural integrity assessment with the identified model is consistent with the stress-triaxiality range observed in the real case of damaged engine shroud. The main result emphasizes the importance of adequate experimental calibration for accurate modelling of structural assessment of aeroengines.

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Keywords: stress triaxiality; Ti-6Al-4V; aeroengines; computational fracture mechanics; fracture strain

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1. Introduction

Ensuring the structural integrity of aeroengines, particularly during catastrophic events like fan blade-out, is paramount for aviation safety. Accurately modeling the behavior of engine materials under extreme loading conditions is crucial to design damage-tolerant components. Fracture stress triaxiality, a critical parameter influencing the maximum deformation and fracture resistance of metals and alloys, plays a significant role in this process (Feng et al., 2024; Skripnyak et al., 2020; Zhang et al., 2021). This is particularly relevant for Ti-6Al-4V, a titanium alloy commonly used in aeroengine manufacturing, as its ability to contain a failed blade is directly related to its fracture stress triaxiality state. Extensive research has been conducted on fan blade out (FBO) events, focusing on turbofan damage assessment (Aveson et al., 2012; Godard et al., 2012; Zhang et al., 2022), containment testing of aeroengines (FAA, 2016; Guo et al., 2020), and the failure mechanisms in aeroengine components, including bolted flanges subjected to impact loading (Cantwell and Morton, 1991; Hassanzadeh et al., 2018). These studies highlight the complexity of FBO events and the need for accurate predictive models to guide the design of damage-tolerant engines.

This paper investigates the influence of fracture stress triaxiality on the damage behavior of Ti-6Al-4V components in aeroengines during FBO events using finite element analysis. We focus on analyzing the deformed outer shroud, a critical component subjected to high stresses during such events. Utilizing the Johnson-Cook damage model, we simulate the FBO scenario and compare the predicted stress triaxiality values with those derived from experimental testing of Ti-6Al-4V specimens. This comparative analysis allows us to assess the model's accuracy in predicting real-world engine behavior. Furthermore, we examine the numerical deformation response of impact-resistant components in the fan blade path, providing valuable data for optimizing aeroengine design and guiding future experimental work for damage model calibration. Our research emphasizes the importance of accurately characterizing fracture stress triaxiality in computational models to ensure the reliability and safety of future aeroengine designs.

2. Materials and methods

This numerical study investigated the behavior of aeroengine components made from Ti-6Al-4V titanium alloy, with a composition of 6.1% Al, 4.0% V, 0.3% Fe, 0.05% N, 0.2% O, 0.08% C, and the balance Ti, as determined via energy-dispersive X-ray spectroscopy. A Johnson-Cook (JC) plasticity model, which is characterized by Young's modulus, initial yield strength, and hardening rate derived from tensile tests conducted at various strain rates and temperatures, was employed to simulate the material's response. The Johnson-Cook damage model was employed to simulate fracture behavior, which is related to fracture strain, stress triaxiality, strain rate, and temperature. The model parameters, which have been previously identified and validated for static and dynamic loading conditions between 25°C and 400°C, are presented in Table 1. Despite the slightly anisotropic nature of Ti-6Al-4V, isotropic behavior of yielding was adopted for simplicity. This simplification prioritizes the dominant effects of strain rate and temperature on yielding behavior of Ti-6Al-4V.

Table 1. Johnson-Cook plasticity and damage model constants for the Ti-6Al-4V alloy (Tuninetti et al., 2024a; Tuninetti et al., 2024b)

Plasticity constants					Progressive constants				
A (MPa)	B (MPa)	C	m	n	d_1	d_2	d_3	d_4	d_5
927.0	878.0	0.0137	0.594	0.795	0.246	186.0	−15.70	0.2582	1.206

Based on previous research focused on turbofan casing dimensions to prevent fracture (Tuninetti and Sepúlveda, 2024), this study uses a similar turbofan model (Fig 1). This model includes complete fixations of the bolt bores, and simulate fan axial rotation with one blade initially detached from the rotor (fan disc). Failure was induced at 1440 rad/s, exceeding the maximum permissible operating speed, to analyze fracture behavior and further ensure the structural integrity of the aeroengine design. The mesh consists of 331,759 nodes and 361,035 combined hexahedral and tetrahedral elements, with refined zones in the impact areas. In this numerical study the focus is on the maximum stress triaxiality ($\eta = p/\bar{\sigma}$; hydrostatic pressure (p) over von Misses stress ($\bar{\sigma}$)) and the strain at fracture reached in the impact zone. This will be compared to the analytical model and experimental data points employed for the calibration of the JC damage model.

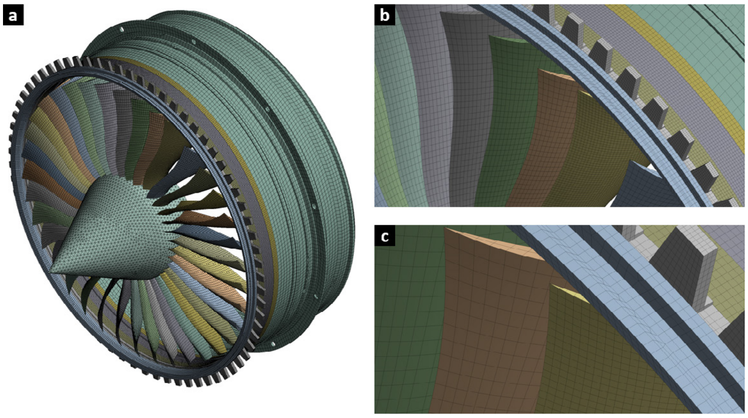

Fig. 1. (a) Discretization mesh of the investigated turbofan model showing detailed views of (b) case and (c) fan blades.

3. Results

Fig. 2a shows the von Mises stress in the aeroengine during a fan blade-out event. The high stress levels reached are 1379 MPa near the fractured zone. The characteristic failure produced by the detachment of a fan blade produces high levels of stress in the surrounding areas of the shroud, causing damage to the alloy components. This impact dynamic is consistent with previously reported results (Tuninetti and Sepúlveda, 2024), but the reliability investigated in this numerical study was observed in terms of the stress triaxiality and strain at fracture, from the theoretical JC model, the experimental data point and the impact dynamics.

Fig. 2b shows the relationship between stress triaxiality and strain at fracture for an alloy. Experimental data and model predictions show that as triaxiality increases, the strain at fracture decreases, indicating a transition to brittle fracture. The contour plot in the upper right of Fig. 2b plots the deformed shape and highlights the areas with different values of stress triaxiality. The regions with triaxiality values of 0.767 appear close to fracture, which is consistent with the experimental strain-triaxiality data range used for the identified Johnson-Cook model.

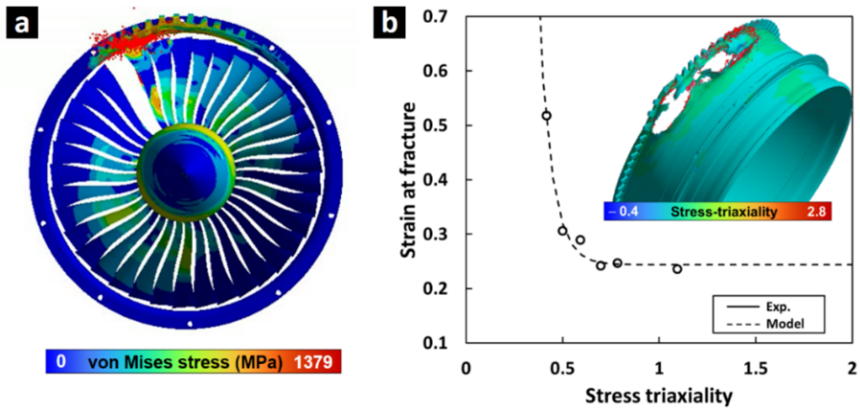

Fig. 2. (a) Finite element simulation of the aeroengine during the loss of a fan blade; (b) Relationship between stress-triaxiality and fracture strain from experiments and JC damage model.

4. Conclusions

This study investigated the applicability of the Johnson-Cook damage model in predicting the damage behavior of a deformed outer shroud during an aeroengine fan blade-out event, focusing on the effect of fracture stress triaxiality on fracture strain. The analytical model's predictions of stress triaxiality versus fracture strain were compared to numerical simulations of a real fan blade-out scenario and the experimental data range used in the model identification. The results show that the identified Johnson-Cook model is capable of capturing the general trend of stress triaxiality evolution in the ranges characteristic of aeroengine failure during a fan blade-out event.

Future research should focus on evaluating the dynamic evolution of the impact phenomena during a fan blade out, performing a rigorous sensitivity analysis of the identified JC model, performing a mesh convergence study on the fracture response, and thoroughly investigating the aeroengine local internal damage in terms of stress triaxiality and fracture strain fields. These investigations will provide further data to optimize the design and manufacturing processes of aerospace components.

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