Post-Print: A Case Study of Typical Hard Landings in Civil Aircraft

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Abstract

Over the past decade, hard landing accidents of civil aircraft have attracted widespread attention. Approximately one-third of civil aircraft safety accidents are related to landing, with hard landing accidents accounting for nearly one-fifth of all landing accidents. Hard landings not only cause damage to aircraft structures, but in severe cases can even lead to aircraft destruction or casualties. However, statistical data on hard landings remains insufficient. This study systematically investigates the determination criteria for hard landings and their damage patterns to aircraft structures through quantitative criteria, simulation analysis, and machine learning methods, and conducts detailed statistical analysis of 53 typical hard landing accidents involving mainstream aircraft models such as the Boeing 737 and Airbus A320 over the past ten years. The results indicate that hard landing accidents typically cause varying degrees of damage to critical components such as the landing gear, fuselage, and wings, and that different types of hard landing accidents exhibit significant differences in the degree of structural damage.

Full Text

Preamble

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Provinces, Member of the Shanxi Provincial General Aviation Industry Alliance Expert Committee. He has presided over 1 National Natural Science Foundation project and over 10 national-level projects, participated in formulating multiple national and international standards, published over 20 high-level academic papers, and applied for over 10 Chinese and international patents. He has received 1 first-class provincial/ministerial award, 3 third-class awards, 2 second-class China Aviation Society Science and Technology awards, 2 second-class AVIC Science and Technology awards, 3 third-class awards, 1 first-class national teaching achievement award, and 1 Shaanxi Provincial special-class teaching achievement award.

Analysis and Research on Typical Cases of Civil Aircraft Hard Landing

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Abstract: Hard landing (also called heavy landing in some regions) poses significant safety risks to civil aircraft operations. Statistical analysis of global civil aviation accidents reveals that while hard landing incidents constitute a relatively low proportion of total accidents, the rate of resulting airframe damage increases substantially. Current determination methods for hard landing events remain inconsistent across the industry. This study systematically investigates quantitative determination standards from major aircraft manufacturers, simulation-based analysis methods, and emerging machine learning approaches. Through comprehensive case analysis of typical hard landing scenarios, we identify critical input parameters for various hard landing conditions and provide detailed assessments of primary impact zones, structural components, and potential damage modes. The research draws upon incident databases including I6 and _6] to compile worldwide cases of civil aircraft hard landings, offering data support for impact dynamics simulation of commercial aircraft. Statistical analysis of 61 hard landing accidents occurring in the past decade indicates that meteorological conditions such as wind shear and gusts, combined with pilot operational factors like excessive approach speed, improper pitch angles, and unstable landing attitudes, represent the primary contributing factors. The study categorizes structural damage patterns into three main types: landing gear damage (including tire blowouts and plastic deformation), fuselage damage (including bulkhead/stringer deformation and tail strikes), and wing damage (including control surface deformation and spar damage). The findings provide a foundation for refined finite element simulation modeling and risk assessment of hard landing events.

Keywords: civil aircraft; hard landing; case analysis; structural damage; determination criteria

1. Introduction

Hard landing (referred to as "heavy landing" in some regions) occurs when an aircraft experiences excessive vertical acceleration or sink rate during touchdown. According to accident statistics from 2011-2020, among civil aviation accidents worldwide, hard landing accidents accounted for approximately [' &] of total accidents. Although the incidence rate of hard landing accidents is relatively low, the proportion resulting in structural damage increases significantly [FIGURE:N]. During this period, hard landing accidents demonstrated varying degrees of airframe damage [FIGURE:N].

Currently, hard landing events may cause passenger discomfort, structural damage, or even casualties. Furthermore, clear determination criteria for hard landing are essential for maintenance decisions and operational safety. With advances in computational capabilities, simulation-based analysis methods have become viable for investigating hard landing events. However, domestic and international research literature on this topic remains scarce. Therefore, this study aims to: (1) identify input parameters for various hard landing conditions through case analysis, and (2) determine primary impact zones, structural components, and potential damage modes. The research analyzes records from databases including I6 and _6] to compile worldwide cases of civil aircraft hard landings, providing data support for impact dynamics simulation of commercial aircraft.

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2. Determination Methods for Hard Landing

2.1 Quantitative Criteria-Based Methods

Boeing Aircraft Maintenance Manual Criteria: For landing weights less than or equal to the aircraft' s design maximum landing weight (non-overweight landings), the limiting sink rate is 10 ft/s. For design takeoff weight (maximum weight in reduced-sink-rate landing conditions), the limiting sink rate is 6 ft/s. For example, the 737 aircraft type has a limit of 600.

Using Newton' s laws, the landing load calculation method is as follows:

$$F = m \cdot \frac{\Delta v}{\Delta t}$$

where m is aircraft landing mass, v is vertical sink rate at touchdown, F is ground reaction force, t is touchdown duration, W is aircraft weight, and g is gravitational acceleration.

Assuming uniform deceleration during touchdown, the landing load calculation method is [MATH_{0047}]. However, hard landing may also occur when the aircraft roll angle exceeds 5° during landing, with specific determination standards varying by aircraft type. Overweight landings, while outside the hard landing category, are closely related to hard landing events.

Airbus Aircraft Maintenance Manual Criteria: For hard landing with landing weight less than or equal to design maximum landing weight (non-overweight), the criteria are: vertical acceleration at the aircraft' s center of gravity greater than or equal to 2.6g, or vertical velocity between 10 ft/s and 14 ft/s. For severe hard landing under similar weight conditions: vertical acceleration at the aircraft' s center of gravity greater than 2.6g, or vertical velocity exceeding 14 ft/s.

From aircraft hard landing analysis, when pitch rate exceeds 5°/s, the aforementioned quantitative determination methods remain applicable. Investigation of hard landing determination standards reveals significant variations across aircraft manufacturers and models. This study adopts Airbus maintenance manual specifications as the reference standard for hard landing determination [FIGURE:N] [FIGURE:N].

2.2 Simulation-Based Determination Methods

Simulation-based methods utilize computer modeling to analyze hard landing events. These methods have seen limited application in full-aircraft hard landing analysis for large commercial aircraft.

Yb et al. [13] employed FEM to evaluate structural integrity of main landing gear and wing components on aging aircraft under various landing angles, revealing stress concentration at the lower side struts of the main landing gear. XO^{6}–I,$\hat{}$ et al. [1(] used coupled CFD-FEM analysis to simulate dynamic processes and structural responses during rotorcraft emergency landing, providing a coupled simulation methodology. 866$\hat{}$8,F]Y,M et al. [2(] analyzed tire structure effects under overweight landing conditions using FEM, demonstrating positive correlation between hard landing severity and aircraft landing weight. N88 et al. [1%(] proposed an efficient simulation method coupling CFD-linear dynamic models with extended inertia relief techniques.

2.3 Machine Learning-Based Determination Methods

Machine learning approaches avoid issues of computational complexity and model assumption limitations. These methods enable real-time monitoring and determination during flight without manual construction of complex physical models, and can adapt to different aircraft types and flight conditions. However, model performance heavily depends on training data quality and quantity, and decision logic remains difficult to interpret.

The machine learning approach involves: (1) collecting data including vertical velocity, acceleration, pitch angle, and altitude; (2) extracting key features for distinguishing hard landings from normal landings; (3) training models using algorithms such as Support Vector Machines (SVM) [13] and neural networks [’ ’ !]1[(]; and (4) validating models using test datasets. This method provides more accurate and detailed assessment compared to traditional vertical velocity threshold methods by evaluating aircraft deformation and loading throughout the landing process.

Model performance comparison shows SVM achieves highest recall rate, though random forest performance is comparable. Random forest models are less affected by imbalanced samples, while neural networks perform poorly due to high training sample requirements and overfitting tendencies [TABLE:N] [FIGURE:N].

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3. Typical Hard Landing Scenarios

This section analyzes factors significantly influencing hard landing events, including meteorological conditions (wind speed, visibility) during approach and landing.

Among 61 hard landing accidents in the past decade, visibility conditions were generally good at the time of incidents. Primary causes included encountering light wind shear during approach and improper pilot manipulation. When wind shear was encountered, improper handling and non-standard operations remained dominant factors, including excessive approach speed, improper pitch angles, and unstable landing attitudes. Half of the accidents occurred under wind shear and gust conditions, typically associated with improper landing attitudes or excessive descent rates. Aircraft wing icing may also lead to excessive vertical velocity during landing.

Typical hard landing scenarios exhibit these characteristics: excessive speed before landing is common. Pilots often reduce power to avoid high speed, but this high pitch attitude may cause tail strikes.

Typical severe hard landing scenarios feature: occurrence under severe adverse weather conditions, rapid changes in velocity/pitch/roll angles during bounce, difficulty for pilots to recover and go-around, and often catastrophic structural damage. Since overweight landings typically involve substantial remaining fuel, they pose serious risks.

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4. Statistical Analysis of Structural Damage Probability

Based on statistics from 61 hard landing accidents in the past decade, primary damage structures and typical damage modes are as follows:

Landing Gear Damage: Most common damage type in hard landing accidents, including tire blowouts, severe plastic deformation of landing gear components, and hydraulic fluid leakage. Hard landing primarily affects aircraft landing gear and fuselage structures.

Fuselage Damage: When aircraft touches down at large pitch angles, the tail may strike the ground, causing bulkhead and stringer plastic deformation, skin abrasion, and wrinkles. The fuselage skin above the nose landing gear may also fracture and deform.

Wing Damage: Severe hard landing may cause wing tearing or rupture, fuel tank damage, and deformation of control surfaces such as ailerons and flaps. Wing spars near the root may also deform.

Engine Damage: Tire debris from blowouts can impact engine blades, potentially causing engine fires.

Other Damage: Flap and spoiler mechanism failures, auxiliary power unit wear.

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5. Case Study Analysis

Table I: Hard Landing Accident Statistics

Accident Severity & Date	Aircraft Damage	Cause Analysis
2011-04-01	Left wing contacted ground	Pilot non-standard operation
2011-04-02	Landing gear and braking system damaged	Pilot reduced power but couldn’ t prevent right wing contact, violating standard procedures
2011-04-03	Severe damage	Overweight severe hard landing, right wingtip contact
2011-04-04	Minor damage	Icing conditions, pilot lost control
2011-04-05	Destroyed	Airport heavy fog, low visibility, left wing fracture
2011-04-06	Severe damage	Wind shear, improper handling
···(additional cases) ···	···	···

Key findings from case analysis: - Wind shear and gust conditions contributed to multiple accidents - Pilot operational errors (excessive descent rates, improper pitch/roll angles) were primary factors - Structural damage severity correlated with vertical acceleration and sink rate - Bounce sequences often led to secondary damage

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6. Conclusions and Future Outlook

1. Statistical analysis of global hard landing accidents reveals meteorological factors (wind shear, gusts) and pilot operational errors as primary causes.
2. Three main determination methods exist: manufacturer quantitative criteria (vertical acceleration/sink rate thresholds), simulation-based analysis (finite element modeling), and machine learning approaches (real-time monitoring).
3. Hard landing significantly impacts landing gear, fuselage, and wing structures. Finite element simulation methods offer explainability and detailed analysis advantages.
4. Future research on civil aircraft hard landing will increasingly rely on finite element simulation technology based on statistical data, balancing computational efficiency with refined modeling of critical areas.

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