ANALYSIS OF ENGINE PYLON STRUCTURAL FAILURE AND ITS IMPACT ON FLIGHT SAFETY:CASE STUDY OF MD-11F (N259UP)

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ABSTRACT — *This study aims to analyze the catastrophic structural failure experienced by a UPS McDonnell Douglas MD-11F (N259UP) cargo aircraft on November 4, 2025, in Louisville, Kentucky. The investigation focused on the detachment of the number 1 engine due to engine pylon failure during takeoff. Through metallurgical analysis and a review of the NTSB investigation report, fatigue cracking in the forward mount fitting was found to be the primary cause of the engine detachment. The results revealed gaps in routine inspection methods for aging aircraft. The study concluded that transitioning to Structural Health Monitoring technology and fleet modernization are crucial risk mitigation measures for the global air cargo industry.*

Keywords: *MD-11F, Engine Pylon, Fatigue Cracking, Aviation Safety, Older Aircraft.*

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1. INTRODUCTION

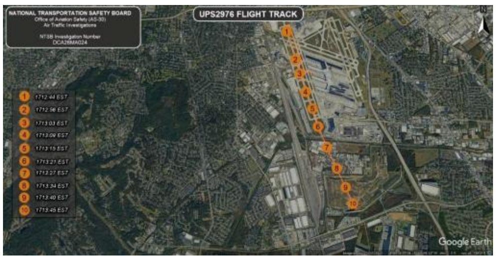
1.1 Background

The air cargo industry is the backbone of global logistics, demanding high reliability. However, the tragic crash of UPS Flight 2976 in late 2025 in Louisville, Kentucky, marked a critical turning point for tri-jet operations in the United States. The McDonnell Douglas MD-11F, a mainstay of cargo airlines for decades, is now under the scrutiny of investigation after experiencing a structural failure, also known as strophic failure: the separation of the number 1 engine during takeoff. This essay will analyze the causal factors, the NTSB investigation process, and the impact of UPS's post-incident policies.

1.2 Research Objectives:

- *Location: Louisville Muhammad Ali Inter national Airport (SDF), Kentucky.*
- *Incident: An MD-11F cargo aircraft (registration N259UP) en route to Honolulu experienced a catastrophic mechanical failure during takeoff.*
- *Engine Detachment: The number 1 (left) engine and its pylon separated comple tely from the wing when the aircraft had only lifted appr*

- *Impact**:** The aircraft lost control, crashed into several industrial buildings (inclu ding a logistics warehouse and an oil recycling facility), and exploded in a large fireball due to its full fuel load.*



1.3. Fatalities

This tragedy is one of the deadliest in UPS air cargo history:

- *Flight Crew: 3 (all crew members on board died).*
- *Ground Casualties: 12 people died as a result of the plane impacting the industrial and residential areas surrounding the airport.*
- *Total Casualties: 15 people died and dozens more were injured.1.4. Temuan Investigasi NTSB (Januari 2026)*

1.4. The preliminary report from the National Transportation Safety Board (NTSB) revealed several crucial points:

- *Fatigue Cracks: Evidence of metal fatigue was found at the connection between the engine pylon and the wing.*
- *Damage History: The investigation found that Boeing (as the holder of the McDonnell Douglas design certificate) had been aware of a potential defect in the engine support as early as 2011, but at the time it was not deemed to pose a safety risk.*
- *Maintenance: The aircraft had just emerged from extensive maintenance in San Antonio a few weeks before the accident, but the cracks were not detected.*

1.5. Impact on the MD-11 Fleet

This incident resulted in major changes to MD-11 operations in the United States:

- *Grounded: Immediately after the accident, the FAA issued an order temporarily grounding the entire MD-11 fleet for an in-depth inspection.*
- *Early Retirement: In January 2026, UPS officially retired its entire remaining MD-11 fleet (approximately 26–28 aircraft) and accelerated fleet modernization with newer aircraft such as the Boeing 747-8 and 767.*
- *Lawsuits: Numerous lawsuits have been filed by victims' families against UPS, Boeing, and the maintenance company for negligence in detecting structural defects in the 34-year-old aircraft.*

1.6. Literature Review

MD-11 Engine Pylon Structure The pylon structure serves as a mechanical bridge between the engine and the wing, designed to withstand thrust, static weight, and dynamic loads. On the MD-11, the engine is suspended using a complex mounting system. The forward mount is a critical component that transfers the primary thrust to the wing structure through high-strength brackets and bolts. Fatigue Phenomena: Fatigue cracks are a major threat to aging aircraft that have exceeded their design lifespan. This process involves three stages: microscopic crack initiation due to cyclical loading, crack propagation due to vibration and air pressure, and cata strophic failure when the material can no longer withstand the load.

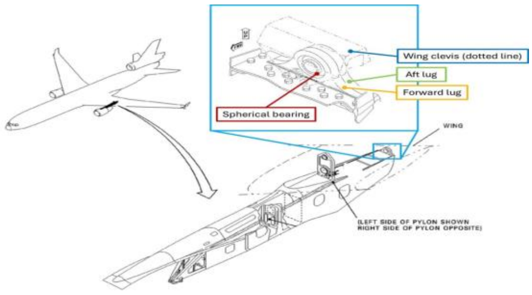
2. *METHODOLOGY*

This research uses a qualitative approach with an investigative case study method. Primary data comes from:

- *NTSB Preliminary Report (January 2026): Regarding the findings of metallurgical evidence in aircraft debris.*
- *Structural Technical Analysis: Through a review of the forward mount design and stress concentration points at the bolt holes.*
- *Historical Document Review: Evaluating Boeing Service Bulletins and FAA Airworthiness Directives related to the pylon defect, which have been known since 2011.*

3. *RESEARCH RESULTS AND DISCUSSION*

Technical Analysis: Engine Pylon Failure
The primary focus of the National Transportation Safety Board (NTSB) investigation was the pylon structure a component that serves as a mechanical bridge between the engine and the wing. On the MD-11, engines 1 and 3 are suspended below the wing using a highly complex mounting system. Metallurgical analysis of the wreckage of N259UP revealed fatigue cracking in the forward mount bolt and pylon fitting. These cracks did not occur suddenly, but rather resulted from the accumulated stress of thousands of flight cycles over the aircraft's 30-year lifespan. This pheno menon was exacerbated by the MD-11's structural design, which has specific dynamic load characteristics in the pylon area. When the cracks reached a critical point, the structure could no longer withstand the thrust and weight of the engines, causing the engines to comple tely separate from the fuselage (detachment).

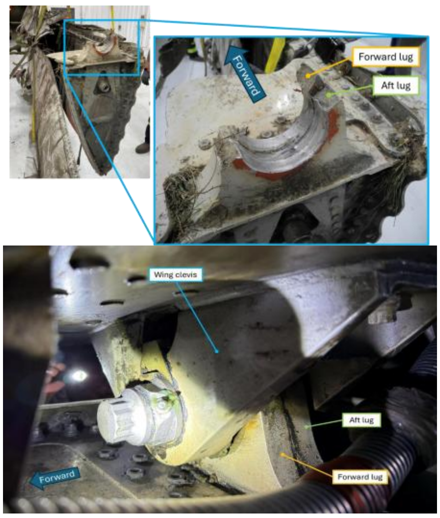


The pylon structure is not simply a support pole, but rather a complex steel and titanium frame designed to withstand thrust, static weight, and dynamic loads during turbulence.

3.1. Anatomy of the Forward Mount (Primary Failure Point)

On the MD-11, the number 1 engine (left wing) is suspended from several primary support points. The Forward Mount is the most heavily loaded component because it must transfer thrust from the engine to the wing structure.

- *Fitting Component: Consists of a "U" or "I" shaped bracket secured with high-tensile bolts.*
- *Stress Concentration Point: The sharp corners or bolt holes in this fitting are areas where stress accumulates. Investigations indicate that the crack originated from one of these bolt holes.*



3.2. Fatigue Propagation Mechanism

Fatigue cracks are the primary enemy of aging aircraft. The process occurred in three stages in the case of N259UP:

- *Initiation: Due to the aircraft's age of 34 years, thousands of takeoff and landing cycles (during which the engines are operating at maximum capacity) created microscopic cracks in the metal surface.*
- *Propagation: Each time the aircraft flies, air pressure and engine vibrations gradually widen these cracks.*
- *Catastrophic Failure: When the remaining area of metal is too small to support the load, it fractures suddenly without warning (brittle fracture).*

3.3. ***The Dynamics of an "Engine Detachment" (Domino Effect)*** *Why did the engine detach completely and not just tilt? This was due to a failed fail-safe design:*

- *Broken Fuse Pin: The original aircraft design typically had a fuse pin designed to break during a crash to allow the engine to separate cleanly without damaging the wing fuel tanks. However, in this case, the fuse pin broke due to the abnormally high load caused by the failure of the front mount.*

Torque and Pitch-up: When the front strut broke, the thrust of the still-running engine pushed the front of the engine upward, creating a huge torque on the rear strut.

- *Total Detachment: The rear strut was not designed to withstand such a large torsional load alone, so it broke within milliseconds.*
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3.4. ***Detection Challenges (Blind Spot Maintenance)***

The investigation also highlighted why these cracks were not discovered during routine maintenance:

- *Hidden Location: The forward mount area is obscured by the aerodynamic panel (fairing) and thermal insulation.*
- *Crevice Corrosion: Cracks are often obscured by corrosion products or paint, so liquid penetrant testing is not always effective unless the component is completely disassembled.*
- *Need for Eddy Current: The NTSB recommended the use of eddy current testing, which is more sensitive to cracks beneath the metal surface, for the entire remaining MD-11 fleet worldwide.*

3.5. *NTSB Investigation and the Role of Maintenance*

The NTSB investigation highlighted two important aspects: the effectiveness of the maintenance program and the manufac turer's technical history. Despite the aircraft having recently undergone a rigorous inspection, the cracks were not detected. This sparked debate about the current non-destructive testing methods used. Whether standard visual and ultrasonic methods are sufficient to detect cracks in the internal parts of the pylon, which is tightly enclosed by the fairing. Furthermore, preliminary reports indicate that there is historical data regarding potential weaknesses in the MD-11 pylon that have been known for decades. The failure to require component replacement (rather than simply inspection) is a crucial point in the liability analysis between the manufacturer and the aviation regulator (FAA)

3.6. *Operational Impact and Strategic Policy*

UPS's response to this accident was drastic but sound from a safety standpoint. The decision to retire the entire MD-11 fleet by early 2026 represents a complete risk mitigation measure. Operationally, the MD-11 offers substantial cargo capacity, but its age-related escalating maintenance costs and the risk of similar structural failures in other aircraft in the fleet undermine its economic value. A rapid transition to a fleet that modern aircraft like the Boeing 747-8F and 767-300F are not just about capacity, but also about adopting more advanced structural health monitoring (SHM) technology, which can provide real-time data on the integrity of critical components without requiring manual structural disassembly.

4. CONCLUSION AND RECOMMENDATIONS

Several conclusions from the research and suggestions that can be recommended by the research team are as follows:

- *The UPS Flight 2976 tragedy provides a harsh lesson for aviation regarding the challenges of operating an aging aircraft fleet. The structural failure of N259UP demonstrated that standard mainte nance procedures are sometimes insuffi cient to combat the natural laws of metal fatigue in aircraft that have exceeded their design lifespan. UPS's decision to end the MD-11 era marks the end of a chapter in the history of cargo aviation and underscores that in this industry, safety must always trump economic efficiency.*

- *Research findings on routine inspection methods for aging aircraft constitute a feasibility study that must be conducted by every company and relevant agency, utilizing technological advancements to identify aircraft developments early before accidents occur.*

- *Utilizing technology to transition to Structural Health Monitoring and fleet modernization is a crucial risk mitigation measure for the global air cargo industry.*

- *Researching the airworthiness of aging aircraft is a concrete first step in maintaining safety and airworthiness*

- *With the utilization of the transition to Structural Health Monitoring technology and fleet modernization is a very important risk mitigation step for the global air cargo industry, which is the main capital to know the extent to which aging aircraft can be used properly..*

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