Submission to the

National Transportation Safety Board

for the

FedEx Express MD-10-10F N391FE Left Main Landing Gear Collapse at Memphis, TN 28 July 2006

The Boeing Company

10 December 2008

INTRODUCTION

On July 28, 2006, about 1125 central daylight time, FedEx Express (FedEx) Flight 630, a Boeing MD-10-10F (MD-10), N391FE, experienced a left main landing gear (MLG) collapse during landing rollout at Memphis International Airport (MEM), Memphis, Tennessee. A fire developed on the left side of the airplane. Airport fire crews responded almost immediately, and the fire was extinguished prior to spreading further. The two flight crew members reported minor sprains and abrasions from the evacuation. A non-revenue FedEx pilot was not injured.

Submission Abstract

- The Boeing Company, as the airplane's manufacturer, is acting as an advisor to the National Transportation Safety Board (NTSB) on technical and operational issues in this investigation.

- The conclusions presented in this submission are based on factual information, Boeing expertise, the use of analytical tools, and a methodical investigation process.

- The left MLG collapse was caused by combined fatigue and stress corrosion cracking of the MLG cylinder assembly. The primary crack initiation point was in an area of stray nickel plating deposits on the bore of the air filler valve port located on the aft side of the MLG cylinder. A secondary crack origination point was a shallow corrosion pit located at the opposite side of the bore to the primary origination point.

- A finite element model (FEM) analysis of the MLG cylinder, an in-service evaluation (ISE) of MLG landing loads on a similar FedEx MD-10 aircraft, fatigue analysis and damage tolerance analysis were performed to evaluate the stresses and strains in the air filler valve area of the MLG cylinder.

- FEM analysis showed that a high drag load braking condition would produce residual tensile stresses in the air filler valve port hole. Stray nickel plating in the bore of the air filler valve significantly reduces fatigue strength at this location. Fatigue analysis using a nickel plate thickness of 0.008" and the residual stress predicted by the FEM showed more than an order of magnitude reduction in the number of flights before cracks would be expected to initiate in the air filler valve port hole.

- Boeing has developed and issued a Service Bulletin and revisions to the Component Maintenance Manual to minimize the possibility of cracks initiating in the bore of the air filler valve and growing to a critical length in the MLG cylinder on DC-10-10/15 and MD-10 airplanes. Boeing also has developed and issued a revision to the Service Bulletin for installation of the DC/MD-10 carbon brake system to improve its performance.

BOEING ASSISTANCE WITH THIS INVESTIGATION

The National Transportation Safety Board (NTSB) is leading the investigation into this FedEx MD-10 accident. Assisting the NTSB in their investigation are the Federal Aviation Administration (FAA), FedEx, the Air Line Pilots Association (ALPA), Boeing, and other designated parties.

As the manufacturer of the MD-10 airplane, Boeing's specific role in this investigation has been to provide technical information regarding the airplane design and operation to assist the NTSB. Additionally, Boeing assisted with the instrumentation, design, and development of the in-service strut loads testing apparatus, developed and refined a FEM of the MLG cylinder with a detailed submodel of the area of the air filler valve, refined the model with the flight test data and known materials characteristics, validated the location of the fracture initiation experienced by the accident airplane using the FEM, performed additional fatigue and damage-tolerance studies as a result of the data obtained from the FEM and in-service test, used the data to develop service action and inspection interval criteria, and provided data regarding these activities to the NTSB. Information transmitted from Boeing to the NTSB in support of this investigation is listed, in part, in a 3-page transmittal letter to NTSB's Airworthiness Group Chairman.[1]

The NTSB requested that all parties submit proposed findings to be drawn from the evidence revealed during the course of the investigation. Boeing is responding to the NTSB request with this document, which:

- Provides an assessment of the evidence and other pertinent data.
- Identifies knowledge gained from the investigation.
- Identifies conclusions supported by the knowledge gained from the investigation.

EVIDENCE ASSESSMENT

The Boeing assessment of the evidence is based upon observations of the airplane and accident site, post-accident examination of airplane systems and components, flight data recorder (FDR) data, the cockpit voice recorder (CVR) transcript, flight crew interviews, metallurgical examination of failed components, in-service recorded flight data, FEM analysis, fatigue analysis, and damage tolerance analysis.

AIRPLANE SYSTEMS

Post-accident investigation revealed no airplane systems-related conditions contributing to the collapse of the left MLG.[2]

Prior to the accident, FedEx worked with Boeing to develop a modified brake system for their MD-10 airplanes that would utilize the same wheels, brakes, and tires used on their fleet of MD-11 airplanes. The MD-11 brake has carbon rotating (rotors) and stationary (stators) disks as

[1] Dodt letter to Crookshanks, 66-ZB-H200-ASI -18338, dated 23 January 2008.
[2] Draft Factual (Long Narrative) pp. 3-4; 10-11

compared to the DC/MD-10 brake, which has steel rotors and stators. The brake system modification installed new antiskid components, MD-11 wheels, tires, and brakes, and modified MLG doors on the MD-10 airplanes via Boeing-issued, FAA-approved Service Bulletins. The carbon brake system did not change the basic operation of the DC-10 brake system. The accident airplane, N391FE, was one of 15 MD-10-10F airplanes converted to the carbon brake system, with N391FE's installation completed in July 2005. The airplane (and left MLG) had accumulated 868 cycles since the carbon brake modification at the time of the accident.[3]

During the investigation it was noted that flight crews of FedEx MD-10 airplanes with the carbon brake system installed had on occasion reported that the carbon brakes had different ramping-up characteristics during brake application than steel brakes, such that crews felt like the carbon brakes were "grabbing" on initial application, a sensation not felt when using steel brakes. Additionally, during the investigation, contamination was noted in the accident airplane's Dual Brake Control Valve (DBCV) with some scoring and scratching of internal components. Inspections of the brake systems of other DC-10F's confirmed the presence of contamination in many aircraft.

Using the pilot reports, data from an instrumented in-service airplane, and a hydraulic simulator, Boeing was able to identify several likely causes for the flight crew reports and develop modifications to the carbon brake system to improve its performance. The modifications included steps to assure clean hydraulic fluid on airplanes with the carbon brake system as well as modifications to the DBCV and Anti-Skid Manifolds (ASM).[4]

The carbon brake system modifications were installed on the instrumented airplane, N357FE, and tested. The test results indicated that the MLG braking response was smooth and did not show any oscillations. The data showed significantly less delay to initiate brake torque, minimal advancing of brake pedals before brake torque initiation, lower initial brake pressure and torque, no significant pressure reductions in multiple brakes, and minimal fore/aft movement of the main gears during braking. Boeing developed and issued a revision to the DC/MD-10 steel to carbon brake Service Bulletin to incorporate the modifications to the carbon brake system. The carbon brake system and brake system improvements are being installed on all MD-10-10F and -30F aircraft.

AIRPLANE STRUCTURES

With the exception of the collapse of the left MLG, the airplane's structures performed as expected during the accident sequence, as evidenced by photo documentation and the Draft Factual (Long Narrative) p. 6.

Photographic documentation of the airplane indicated that the left engine pylon structure responded as expected for the condition of a collapsed left MLG.

Optical examinations of the fracture faces in the left MLG cylinder found chevrons and other markings indicating that the overall separation initiated at individual locations on the inboard and outboard sides of the air filler valve hole located on the aft side of the cylinder. Close

[3] Draft Factual (Long Narrative) p. 5
[4] Draft Factual (Long Narrative) pp. 10-11

examinations established that the chevron markings led back to initiation sites on the smooth, unthreaded portion of the air filler valve hole inner diameter. Discontinuous and spotty nickel plating was noted on portions of the air filler valve hole bore. Nickel plating is allowed for repairs in the bore of the outer cylinder but not in the air filler valve hole. The two fractures, referred to as the inboard and outboard fractures propagated separately around the cylinder, joined at the forward side and separated the outer cylinder into two main pieces. Away from the air filler valve hole, the fracture features were typical of overstress separations in high strength steel.

At the initiation site for the outboard fracture, a slightly darkened thumbnail-shaped fracture region was observed at the outboard side of the air filler valve hole, centered about 0.20 inch from the projected inner diameter of the cylinder. The thumbnail region measured about 0.13 inch along the hole bore and about 0.025 inch deep. The bore surface adjacent to the thumbnail was covered with a 0.008 inch thick layer of nickel plating.[5] The plating appeared tightly adherent to the bore and was fractured in-plane with the cylinder separation. Scanning electron microscope (SEM) examinations in conjunction with energy dispersive x-ray spectrography (EDS) revealed an oxide layer on the thumbnail region at the outboard side of the hole. The fracture features within the thumbnail were a mixture of intergranular and transgranular separations, consistent with stress corrosion cracking and with fatigue propagation respectively.

Examinations on the inboard fracture initiation area revealed a single point initiation on the bore surface approximately 0.14 inch from the projected inner diameter of the cylinder. SEM viewing uncovered a small spherical corrosion pit at the initiation but no plating and a small semicircular region of transgranular fatigue features surrounding the pit.

The smooth portion of the air filler valve hole displayed a fine surface finish with no machining tears or marks. Some corrosion pits up to 0.002 inch in diameter were noted in this area as well as corrosion pitting in the unplated band on the inner diameter of the cylinder at the location of the hole.

The diameter of the smooth portion of the hole was estimated based on measurements of the radius of the segments of the hole contained in the metallographic sections. From these measurements, the hole diameter was estimated to be between 0.453 and 0.462 inch. The engineering drawing specifies a 0.4460 to 0.4537 inch diameter hole. Hardness measurements were also made on the metallographic samples. They ranged from HRC 53.8 and 55.3 and averaged 54.5 HRC. The drawing specifies the material to be heat treated to 275,000 to 305,000 psi ultimate tensile strength with a hardness of 53 to 56 HRC. EDS spectra acquired during SEM viewing of the fracture face was consistent with the specified material, 300M alloy steel.[6]

An ISE of MLG loads was conducted by installing instrumentation on the MLG of a FedEx MD-10 airplane similar to the accident airplane. The main purpose of the evaluation was to determine the typical loads imparted to the MLG during the landing sequence. A FEM of the

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[5] The MLG outer cylinder was last overhauled in July 2005. Records of the work performed indicate that nickel plating was applied to the inner diameter of the cylinder. Airworthiness Group Factual Report Addendum 3. The stray nickel plating on the bore surface was most likely introduced during overhaul, whether in July 2005 or an earlier overhaul.

[6] Draft Factual (Long Narrative) pp. 7-8

300M steel MD-10 MLG cylinder with a detailed submodel of the area of the air filler valve also was developed. The FEM was used to analyze the stresses on the MLG cylinder in the area of the air filler valve under the actual measured landing loads on the ISE airplane.

FEM analysis of a high drag load braking condition showed that a 47 KSI residual tension stress could be produced in the air filler valve port hole. It is well known that nickel plating reduces the fatigue strength of 300M steel, the MLG outer cylinder material. Previous testing of 300M steel done by Boeing reveals that with a nickel plating thickness of 0.008", an equivalent stress ***increase*** factor of 1.35 results.[7] Boeing performed fatigue analysis using both the certification fatigue spectrum and the ISE fatigue spectrum with a nickel plate thickness of 0.008" in the air filler valve bore and the residual tension stress of 47 KSI. The analysis showed that for both fatigue spectrums analyzed the nickel plate caused more than an order of magnitude reduction in the number of flights before cracks would be expected to initiate in the air filler valve port hole.

As a result of the FEM analysis and the fatigue analysis, Boeing developed instructions and recommendations for inspecting the air filler valve bore for the presence of stray nickel or chrome plating deposits, corrosion or cracks and for repair or replacement of the MLG outer cylinder assembly in the event any of these conditions are found. Boeing performed additional damage tolerance analysis to establish appropriate recommended initial inspection times and repeat inspection intervals. Boeing issued Alert Service Bulletin DC-10-32A259 on October 30, 2007 for the recommended inspection of the bore of the air filler valve port on all DC-10-10, DC-10-10F, DC10-15 and MD-10 airplanes. Boeing also issued revisions to the Component Maintenance Manual for these airplanes to provide instructions relating to the recommended inspection and protection of filler valve hole from deposits of stray nickel/chrome plating during plating of the MLG cylinder.

LEFT ENGINE NACELLE AND INBOARD WING FIRE

Prior to the airplane stopping, a fire ignited beneath the left engine nacelle and spread to the inner portion of the left wing. The captain activated the left engine fire extinguisher and began shutting down the airplane. Airport fire crews responded almost immediately, and the fire was extinguished prior to spreading further.

When the airplane came to rest, the left side of the airplane was supported by the left nacelle, the left wing outboard flap hinge fittings, and the left wingtip while the right side was resting on the right main landing gear (RMLG) inboard tires. The left engine aft mount was fractured and the left engine was canted upwards about the forward mounts. The left engine pylon structure responded as expected for the condition of a collapsed left MLG.

The fire consumed the number 3 slat, the inboard end of the number 4 slat, the left and upper portions of the left nacelle, and the left side of the engine case. The remainder of the left wing and nacelle sustained moderate to heavy fire damage. There was some minor sooting to the left fuselage in the vicinity of the wing attach area. Fire did not spread into the interior portions of the airplane.[8] The left wing fire was the result of the engine nacelle dragging on the runway in

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[7] Draft Factual (Long Narrative) p. 10.
[8] Draft Factual (Long Narrative) pp. 2, 6

combination with jet fuel leakage from damage to the engine and/or pylon structure. There were no reports of fuel leakage from the left wing fuel tanks.[9] [10]

ESCAPE SLIDES

The crew and nonrevenue pilot evacuated the airplane via the R1 door and slide. The crew reported that due to the leftward list of the airplane, the slide was at a steeper angle than normal. The two flight crew reported minor abrasions and sprains from the evacuation, but no serious injuries.[11] The non-revenue FedEx pilot did not report any injury.

AIRPLANE PERFORMANCE

Examination of the flight data recorder (FDR) data, crew interview transcripts, and the Cockpit voice recorder (CVR) transcript revealed the accident landing was unremarkable and within normal operational parameters.[12]

KNOWLEDGE GAINED DURING THE INVESTIGATION (Findings)

The following summarizes knowledge gained that is pertinent to drawing conclusions:

- The left MLG collapse was caused by combined fatigue and stress corrosion cracking of the MLG cylinder assembly.
- FEM analysis of a high drag load braking condition produced residual tensile stresses in the air filler valve port.
- Stray nickel plating in the bore of the air filler valve significantly reduces fatigue strength at this location resulting in a reduced fatigue life for the cylinder. Fatigue analysis indicates that the expected number of flight cycles prior to initiation of cracks is reduced by an order of magnitude due to the presence of stray nickel in the air filler valve bore.
- The left engine pylon responded as expected for the condition of a collapsed left MLG..
- The left wing fire was the result of the engine nacelle dragging on the runway in combination with jet fuel leakage from damage to the engine and/or pylon structure.

CONCLUSIONS

Boeing believes that the evidence supports the following conclusions for the accident:

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[9] Airworthiness Group Factual Report p. 2
[10] Operations Group Chairman's Factual Report Attachment 1 pp. 1-14
[11] Draft Factual (Long Narrative) p. 2
[12] Draft Factual (Long Narrative) p. 7

The cause of the accident was the collapse of the left MLG caused by combined fatigue and stress corrosion cracking of the MLG cylinder assembly. Stray nickel plating (most likely introduced during overhaul) in the air filler valve port hole significantly reduced fatigue strength of the 300M steel and likely led to the initiation of cracks in the valve hole.

RECOMMENDATIONS

Boeing has no further recommendations. Corrective actions have already been issued and are being implemented.

BOEING ACTIONS

As a result of this investigation, Boeing has:

- Issued Service Bulletin DC10-32A259 on October 30, 2007, mandated by FAA Airworthiness Directive 2008-09-17 on May 2, 2008

- Revised Main Landing Gear Shock Strut Assembly CMM Chapters 32-11-01 and 32-11-04, September 15, 2007

- Revised DC/MD-10-10F and DC/MD-10-30F Service Bulletins DC10-32-258 and - 257, respectively (replaces steel brakes with carbon brakes) to enhance carbon brake dynamic characteristics. Both bulletins were originally issued in September of 2005, and were updated in February, 2008.