National Transportation Safety Board
Aviation Accident Final Report

Location:	Memphis, TN	**Accident Number:**	DCA06FA058
Date & Time:	07/28/2006, 1125 CDT	**Registration:**	N391FE
Aircraft:	BOEING MD-10-10F	**Aircraft Damage:**	Substantial
Defining Event:		**Injuries:**	3 None
Flight Conducted Under:	Part 121: Air Carrier - Non-scheduled		

Analysis

The approach and landing were stabilized and within specified limits. Recorded data indicates that the loads experienced by the landing gear at touchdown were within the certification limits for an intact landing gear without any pre-existing cracks or flaws. The weather and runway conditions did not affect the landing. The application of braking by the accident crew, and the overall effect of the carbon brake modification did not initiate or contribute to the landing gear fracture. Post-accident modifications to the MD-10 carbon brake system were implemented due to investigative findings for the purposes of braking effectiveness and reliability. Post accident emergency response by the flight crew and ARFF was timely and correct.

The left main landing gear (LMLG) outer cylinder on the accident airplane had been operated about 8 ½ years since its last overhaul where stray nickel plating likely was introduced in the air filler valve hole. Nickel plating is a permissible procedure for maintaining the tolerances of the inner diameter of the outer gear cylinder, however the plating is not allowed in the air filler valve bore hole. Literature and test research revealed that a nickel plating thickness of 0.008" results in a stress factor increase of 35%. At some point in the life of the LMLG, there was a load event that compressively yielded the material in the vicinity of the air filler valve hole causing a residual tension stress. During normal operations the stress levels in the air filler valve hole were likely within the design envelope, but the addition of the residual stress and the stress intensity factor due to the nickel increased these to a level high enough to initiate and grow a fatigue crack on each side of the air filler valve hole. The stresses at the air filler valve hole were examined via development of a Finite Element Model (FEM) which was validated with data gathered from an instrumented in-service Fedex MD-10 airplane. The in-service data and FEM showed that for all of the conditions, the stress in the air filler valve hole was much higher than anticipated in the design of the outer cylinder. Fatigue analysis of the in-service findings and using the nickel plating factor resulted in a significantly reduced fatigue life of the gear cylinder compared with the certification limits. During the accident landing the spring back loads on the LMLG were sufficient to produce a stress level in the air filler valve hole that exceeded the residual strength of the material with the fatigue cracks present.

Probable Cause and Findings

The National Transportation Safety Board determines the probable cause(s) of this accident to be: the failure of the left main landing gear due to fatigue cracking in the air filler valve hole on the aft side of the landing gear. The fatigue cracking occurred due to the presence of stray nickel plating in the air filler valve hole. Contributing to this was the inadequate maintenance procedures to prevent nickel plating from entering the air filler valve hole during overhaul.

Findings

Occurrence #1: GEAR COLLAPSED
Phase of Operation: LANDING - ROLL

Findings
1. (C) LANDING GEAR,MAIN GEAR STRUT - FAILURE
2. (F) MAINTENANCE,OVERHAUL - INADEQUATE - OTHER MAINTENANCE PERSONNEL

Factual Information

HISTORY OF FLIGHT

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 failure immediately after landing at Memphis International Airport (MEM), Memphis, Tennessee. The left main landing gear (LMLG) collapsed after touchdown on runway 18R, and the airplane came to rest on the left side of the runway. After the gear collapsed, a fire developed on the left side of the airplane. The two flight crewmembers received minor injuries during the evacuation, and one nonrevenue FedEx pilot was not injured. The postcrash fire substantially damaged the airplane's left wing and portions of the left side of the fuselage. Flight 630 departed from Seattle-Tacoma International Airport (SEA), Seattle, Washington, and was operating under the provisions of 14 Code of Federal Regulations (CFR) Part 121 on an instrument flight rules flight plan.

The crew stated that the takeoff and departure from SEA were normal with very little traffic that day, there were no issues with the airplane en route from SEA to MEM and there were no weather deviations. Approaching MEM, air traffic control (ATC) vectored the flight onto the runway 18R final approach course. The flight was then cleared for a visual approach to runway 18R. The visual approach was initially flown with the autopilot engaged and coupled to the instrument landing system (ILS). The airplane was established on the final approach course about 9 miles north of the airport. About 1,600 feet altitude, the airplane was configured for a flaps 35 landing and the approach was stable passing through 1,000 feet. The crew reported that gusty winds at altitude reduced to near calm, or a light tailwind, by this point.

The crew reported the final approach segment was smooth, and the first officer disengaged the autopilot at approximately 400 feet and manually flew the airplane appropriate to conditions. He noted that some crosswind correction was still required at approximately 50 feet, when the electronic altitude callout cadence began. He stated that the flare and touchdown were normal, with crosswind correction. The airplane landed with 122 knots airspeed and a descent rate of approximately 2 to 3 feet per second (fps). A Safety Board performance study concluded that the touchdown was within design limits for the main landing gear (see Tests and Research).

Approximately seven seconds after touchdown, FDR data and performance calculations indicated that the LMLG began to fail (collapse), which was coincident with the location of the ground scar marks on the runway. The first officer reported that while actuating the thrust reversers, he started to apply brakes and immediately experienced "a severe and violent shudder" much more violent than he had ever experienced. He released the brakes, and the shuddering continued, but less violently, and he then reapplied brakes and the shuddering increased again. At that time, the airplane rolled and yawed to the left. The first officer held full right yoke and full right rudder in an effort to counter the turning and listing. The captain tried to assist by using the tiller to keep the airplane on the runway. The airplane continued yawing and sliding to the left and came to rest close to taxiway M4.

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.

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.

INJURIES TO PERSONS

The crew reported minor abrasions and sprains from the evacuation. No serious injuries were reported.

DAMAGE TO AIRPLANE

The airplane came to rest on the left side of Runway 18R at the M4 taxiway, about 6,050 feet from the approach end of the runway. The LMLG collapsed during the accident sequence and was folded aft with the strut in a horizontal position and the truck beam in a vertical position. The truck beam positioning actuator was fractured at the truck beam and the axles were in the normal positions. The aft tires of the LMLG impacted the left inboard flap, damaging it and deforming it upwards. The left side of the airplane was resting on 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 nose landing gear (NLG) was intact and turned to the right about 20 degrees and was resting on only the left tire. No tread remained on the left NLG tire, some of the reinforcing plies were showing, and there was cross-wise scuffing. The right NLG tire appeared essentially normal. The RMLG was intact with the two inboard tires contacting the ground. The RMLG forward, inboard tire tread was considerably worn while the other three appeared essentially normal. The rest of the airplane was undamaged. The flaps and slats were in the deployed position and the left engine thrust reverser was in the deployed position. The right engine thrust reverser was in the stowed position.

A post crash fire ensued on the left side of the airplane consuming 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. Memphis Airport Rescue and Firefighting responded to the accident within four minutes. Fire did not spread into the interior portions of the airplane.

The outer cylinder of the LMLG was fractured through the air filler valve boss on the aft side of the outer cylinder. The fracture continued around the circumference of the outer cylinder at the same level for about 240 degrees. The fracture then turned upwards and continued around the remaining circumference about 5 inches above the level of the filler valve on the forward side of the outer cylinder. A piece of the outer cylinder about 5 inches high by 8 inches wide was recovered on the runway. The LMLG lower side brace remained attached to the lower outer cylinder and the upper side brace was twisted about 90° along its length. The LMLG retract actuator was in the extended position and the rod end was fractured. The LMLG lock links were fractured.

OTHER DAMAGE

None

PERSONNEL INFORMATION

The two crewmembers had never flown together before this flight pairing, which began on July

26, 2006. On the first day, they flew MEM-SEA, followed by a layover at SEA. On the second day, July 27, 2006, they went SEA-Oakland, California-SEA, followed by another layover. The first flight on the third day, July 28, 2006, SEA-MEM, was the accident flight.

The Captain, age 57, held airline transport, flight instructor, and commercial pilot certificates, with multi-engine land and single-engine land ratings. She was type rated in the Falcon 20, Boeing 727, DC-10 and MD-10/11. The MD-10/11 type rating was issued in November 1993. She was hired by FedEx in February, 1979. Her total flight time was approximately 16,000 hours with 4,223 hours as pilot-in-command in the MD-10/11. She had flown 116 hours, 31 hours, and 6 hours in the last 90 days, 30 days, and 24 hours, respectively prior to the accident flight. Her last line check was in the MD-11 on July 19, 2006. The captain reported that she had served as a check airman on the MD-10/11 between 1997 and 2002. She held a first class medical certificate with a limitation for glasses for intermediate and near vision, and her last medical examination was on July 19, 2006.

A review of FAA records indicated no history of failures or re-tests for FAA airman certificates and ratings. A search of FAA and company records revealed no FAA enforcement actions, incidents, accidents, or company disciplinary actions for the captain.

The First Officer, age 38 held an airline transport certificate, with a multi-engine land rating. He was type rated in the MD-10/11. The MD-10/11 type rating was issued in December, 2005. He was hired by FedEx in April 2004. His total flight time was approximately 5,000 hours with 300-350 second-in-command hours in the MD-10/11. He had flown 90 hours, 38 hours, and 6 hours in the last 90 days, 30 days, and 24 hours, respectively prior to the accident flight. His last line check was in the MD-11 on April 23, 2006. He held a first class medical certificate with no limitations, and his last medical examination was on March 2, 2006. The First Officer reported that he flew the C-17 for 4,000 hours while on US Air Force active duty for 13 years and was currently flying the C-17 in the USAF Reserves.

A review of FAA records indicated that a Notice of Disapproval of Application was issued on December 3, 2005, for an MD-10/11 Type Rating. He subsequently passed the test and was issued a Temporary Airman Certificate on December 8, 2005. A search of FAA and company records revealed no FAA enforcement actions, incidents, accidents, or company disciplinary actions for the first officer.

AIRPLANE INFORMATION

The accident airplane, N391FE, S/N 46625, an MD-10-10F series airplane, was equipped with three General Electric CF6-6D engines, and had been converted from a DC-10-10F to an MD-10-10F in May 2002. According to FedEx records, the accident airplane had 73,283 total hours and 27,002 cycles at the time of the accident. According to the dispatch documents for the accident flight, the airplane's takeoff weight was 341,069 pounds. The airplane's estimated landing weight was 284,069 pounds, with a center of gravity (CG) of 18.8% mean aerodynamic chord, including about 43,595 pounds of cargo and about 25,300 pounds of fuel. FedEx documents indicated that the airplane's maximum landing weight was 374,500 pounds. According to the documents and post accident examination, no hazardous cargo was on board the airplane.

The flight manual indicated that for this weight, and a flaps 35 landing configuration, Vref speed should be 126 knots indicated airspeed.

Main Landing Gear Outer Cylinder

According to the FedEx airplane status report, the LMLG outer cylinder had accumulated 33,148 cycles since new at the time of the accident. However, numerous discrepancies were found between various LMLG records. Further examination of the records revealed that this number was higher than the true number of cycles on the outer cylinder but no accurate number of cycles could be established. The records for all work performed during the July, 2005 overhaul were recovered, and of note was the application of nickel plating to the inner diameter of the cylinder (see Airworthiness Group Factual Report Addendum 3 for the detailed work orders.)

Brake System

The dual redundant brake system is similar in arrangement and function on all DC-10, MD-10, and MD-11 airplanes. The major components of the system are the brake pedals (left and right) coincident with the rudder pedals at the captain's and first officer's positions in the cockpit, the two dual brake control valves (DBCV), installed in the left and right main landing gear (MLG) wheel wells, the four anti-skid manifolds (ASM), two each on the left and right MLG's, and the eight brake assemblies, one on each MLG wheel. Each brake is actuated by 8 brake pistons connected to two independent hydraulic systems, 4 pistons on each system. The brakes are activated by depressing the upper portion of the rudder pedals from either pilot position. The left brake pedals and right brake pedals are mechanically connected together beneath the cockpit floor. Two separate left pedal cable loops and two separate right pedal cable loops each mechanically operate the input lever of one side of one DBCV. Each DBCV receives 3000 psi hydraulic fluid from two separate aircraft hydraulic systems. In response to input lever movement, the applicable side of each DBCV meters the 3000 psi hydraulic fluid to the output port, regulating the line pressure ("metered pressure") in proportion to brake pedal travel. Each metered pressure fluid output is connected to one of the four ASM's. Inside each ASM are four antiskid valves, each ported/connected to 4 pistons of one brake. Each antiskid valve is independently and electrically controlled by the Antiskid Control Unit, which when commanded, reduces the DBCV metered pressure ported to the 4 pistons of the applicable brake. The ASCU takes information from the wheel speed transducers and automatically reduces the pressure applied to the brakes to prevent a skid.

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 opposed 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 under a FAA-approved Boeing Service Bulletins. The accident airplane, N391FE, was one of 15 MD-10-10F and MD-10-30F airplanes converted to the carbon brake system. The carbon brake system was installed on N391FE in July 2005. The carbon brake system did not change the basic operation of the system described above. The airplane (and LMLG) had accumulated 868 cycles since the modification at the time of the accident.

METEOROLOGICAL INFORMATION

The Memphis Surface Observation nearest to the approximate time of the accident (1625 UTC) was as follows:

Memphis special report at 1630 UTC, wind from 270 degrees true at 14 knots gusting to 18 knots, visibility unrestricted at 10 statute miles, a few clouds at 7,500 feet, scattered clouds at

10,000 feet, overcast at 15,000 feet, temperature 26 degrees Celsius (C) (79 degrees F), dew point 18 degrees C (64 degrees F), altimeter 30.15 inches of mercury (Hg). Remarks: automated observation system.

Between 0945 UTC and 1529 UTC rain was reported at the airport, with approximately 0.05 inches reported.

AIRPORT INFORMATION

Memphis International Airport is located about three miles south of Memphis, Tennessee. The airport has three parallel north/south runways and one east/west runway. The parallel runways are numbered 36L-18R, 36C-18C, and runway 36R-18L. The non-parallel runway is numbered 9-27. The airport elevation is 341 feet above mean sea level (MSL).

Runway 36L-18R is constructed of grooved concrete and is 9,320 feet long, and 150 feet wide. The 18R touchdown zone is at 293 feet MSL. It is equipped with an instrument landing system approach, medium intensity approach lighting system with runway alignment indicator (MALSR), and there is no visual approach slope indicator. The ILS glideslope is unusable below 500 feet (200 feet above the runway) due to the bending in the glideslope electronic beam.

FLIGHT RECORDERS

The accident airplane was equipped with a Honeywell 6022 SSCVR 120 Cockpit Voice Recorder, Serial Number 04845. This is a solid-state CVR that records two hours of digital cockpit audio. Upon arrival at the NTSB audio laboratory, it was evident that the CVR had not sustained any heat or structural damage and good-to-excellent quality audio information was extracted from the recorder normally, without difficulty. A cockpit voice recorder group was convened at the NTSB audio laboratory and a partial transcript was produced.

The accident airplane was equipped with a Honeywell Model 980-4700, 256 Word Solid State Flight Data Recorder, Serial Number 5326. The recorder was in good condition and the data were extracted normally. The Honeywell Solid State Flight Data Recorder (SSFDR) records airplane flight information in a digital format using solid-state flash memory as the recording medium. The SSFDR can receive data in the ARINC 573/717/747 configurations and can record a minimum of 25 hours of flight data. The system was found to be in compliance with the requirements of 14 CFR Part 121 with the exception of the sampling interval for the four aileron position parameters. There is no indication that any data was lost, and this parameter was not necessary for the tests and research cited below.

WRECKAGE AND IMPACT INFORMATION

The first piece of accident debris on the runway was a small section of the threaded portion of the air filler valve boss normally located on the aft side of the LMLG outer cylinder. The piece was found about 3,430 feet from the approach end of the runway. The filler valve normally installed in the boss was found about 3,713 feet from the approach end of the runway. The 5 by 8 inch section of LMLG outer cylinder (previously described) was found about 3,915 feet from the approach end of the runway. Several other pieces of debris including a piece of the upper piston stop, the LMLG proximity target, the LMLG auxiliary spacer, LMLG door fragments, and various pieces of the inner cylinder were found on the runway between the filler valve boss and the airplane. The upper piston stop, auxiliary spacer and upper chamber all exhibited compression damage.

Several scrapes and gouges were evident on the runway corresponding to various components of the left wing contacting the runway after the collapse of the LMLG. These marks could be followed from their point of first appearance to the point where the aircraft came to rest. The left nacelle first contacted the runway about 3,486 feet from the approach end. The left wing outboard flap, outboard hinge fitting first contacted about 3,498 feet from the approach end while the inboard hinge fitting contacted about 3,512 feet from the approach end. The left wingtip first contacted the runway about 3,499 feet from the approach end of the runway.

MEDICAL AND PATHOLOGICAL INFORMATION

Toxicology testing on the crew was conducted by the company for alcohol by a breath test, and for major drugs of abuse by a urine sample on July 28, 2006. All tests were negative.

TESTS AND RESEARCH

Performance Study

A Safety Board performance study was conducted to determine the aircraft's landing performance, descent rate, and the loads on the LMLG. The study found that about seven seconds after touchdown, the vertical load factor decreased to about 0.6 G and then 1 second later increased to about 1.7 G's. The increase was most likely a result of the failure (collapse) of the LMLG and was consistent with the location of the ground strike marks of the engine cowling and wing tip. The maximum lateral load of approximately 0.3 G during the landing roll was determined to be within the design and ultimate load limits. Calculations of vertical speed showed that the flight landed with a sink rate between 2 and 3 fps. Drift angle at 1.5 seconds prior to touchdown was calculated at 2 degrees to the east, with a crosswind from the west of 8 knots. At touchdown the drift angle was zero degrees.

The loads on the LMLG during landing and roll out were calculated and showed that the design limits were not exceeded for an intact LMLG without any pre-existing cracks or flaws.

Materials Lab

Portions of the Left Main Landing Gear Outer Cylinder were sectioned from the wreckage and brought to the NTSB materials laboratory. Examinations confirmed the visual indication that the outer cylinder fracture initiated at the air filler valve boss (also known as Schraeder valve) just below the aft drag brace arm. The outer cylinder was fractured into two large pieces comprising the upper and lower portions of the cylinder and two smaller pieces. One of the small pieces was from the lower half of the air filler valve boss; the other was a portion of the cylinder wall from the forward side of the cylinder. The separated air filler valve was also retrieved.

Optical examinations of the fracture faces 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. Close 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. 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.

In-Service Evaluation

The Airworthiness Group proposed an In-Service Evaluation (ISE) of the MLG loads on a FedEx MD-10-10F airplane similar to the accident airplane. The main purpose of the evaluation was to accurately determine the loads imparted to the MLG during the landing sequence and to validate the finite element model of the MLG that was being developed. A flight test proposal was developed and in cooperation with FedEx management, aircraft N357FE was selected as the candidate airplane. The MLG instrumentation was installed on the airplane during scheduled maintenance. Each landing gear was instrumented with 8 linear strain gages, 3 rosette strain gages, 1 tri-axial accelerometer, and 1 brake pressure transducer. The airplane was instrumented with 1 tri-axial accelerometer near the center-of-gravity, 2 brake pressure transducers, one each on the left and right brake systems, and two string potentiometers, one each on the left and right DBCVs. All of the data was fed to a recording device in the central avionics compartment where it was recorded at 200 Hz. The airplane was routed through Memphis periodically so that the data card could be swapped out and downloaded. The airplane gathered data in revenue service for about four months.

The instrumentation was calibrated during static run ups of the two wing engines to specified

N1 percentage settings. After the engine runs the airplane was jacked up to obtain the no-load reading for all of the instrumentation. This zero offset value for the strain gages was used to adjust the in-service strain values.

The recorded data from the ISE flights was validated to remove bad or incomplete data sets and stored in individual spreadsheet files for ease of manipulation. A total of 266 flights produced useable braking data and 237 flights produced useable touchdown data. After corrections and calculations were applied, a maximum drag load of about 100 kips (1,000-pounds) was evident on both the right and left MLG.

Finite Element Model

In order to accurately determine the stresses in the vicinity of the air filler valve bore, the airworthiness group developed a finite element model of the MD-10-10F main landing gear (MLG). A detailed submodel of the area of the air filler valve was also developed to accurately model the stress and strain in this area. The model was calibrated using the data from the static engine run-ups performed as part of the ISE instrumentation calibration. The calculated strains from the FEM ranged about 8% to 20% lower than the strains measured with the instrumentation. The average under prediction was about 14%. The calculated stresses outputs from the FEM were therefore increased by 10% to correlate with the actual measured loads on the in-service aircraft MLG. The certification landing and braking load spectrums were used as inputs to the FEM to develop the correlation between strain at the ISE measurement locations and the strain in the air filler valve hole. The FEM results showed that for all of the conditions, the stress in the air filler valve hole was much higher than anticipated in the original design of the outer cylinder.

A certification fatigue condition with the drag load, due to braking, set to 100 kips was run in the Finite Element Model. This condition produced a minimum principal stress (maximum compressive stress) of about -260 ksi (kilopounds per square inch) at the 3 and 9 o'clock positions in the hole and an equivalent plastic strain of about 0.0023. For purposes of the analysis, the known value of the tensile yield stress of 220 ksi was used for the compressive yield stress. These results indicated the material had been compressively yielded in local areas around the hole. The model was unloaded and revealed a residual tension stress of about 47 ksi at the 3 and 9 o'clock positions inside the hole, penetrating to a depth of about 0.025". The fatigue analysis used a most-adverse assumption that the residual tension stress was present in the air filler valve hole from the beginning of the operational life of the outer cylinder.

Fatigue Analysis

A fatigue analysis of the certification and ISE loads was performed for the cases of no nickel and a 0.008" layer of nickel in the hole. An additional factor necessary to perform the fatigue analysis was the effects of the stray nickel plating found within the bore hole. As detailed in the materials lab examination above, a 0.008" layer of nickel was found in the air filler valve hole at the point of outboard crack initiation. There is no nickel plating applied to the MLG outer cylinder during initial manufacture but the Component Maintenance Manual (CMM) allows for nickel plating of certain areas of the outer cylinder as a repair for worn areas at the seals or bearings. The allowed nickel is then over plated with chrome. The nickel did not completely cover the entire diameter of the hole, was of varying thickness, and had a somewhat splattered appearance. Research into the effect of nickel plating on 300M steel was conducted. According to the American Society of Materials Metals Handbook, Volume 2, 8th Edition, "Chromium, iron, and nickel plating generally contain high residual tensile stresses, which reduce the fatigue strength of the base metal of a shaft." In the late 1970's Boeing performed a study on the effects of chromium and sulfamate nickel plating on the fatigue strength of 300M steel. The testing revealed that with a nickel plating thickness of 0.008" a stress factor of 1.35 results. This factor was applied to all MLG hole stresses for the purposes of the fatigue analysis. The RMLG was used as the most-adverse assumption for the fatigue analysis because the in-service data indicated about 5% of the total number of occurrences on the RMLG occur at a level of 100 ksi or greater while only about 0.9% and 0.8% of the occurrences for the LMLG and certification, respectively, are at or above 100 ksi. There was no separate fatigue analysis due to braking at the hole location performed during certification of the airplane since the major loads are compressive in nature and the hole was not critical during the full-scale fatigue test. Using the RMLG from the ISE data with the 47 ksi residual stress and nickel present in the air filler valve hole, the analysis yielded a fatigue life of 8,503 cycles, which is well below the certification safe life limit of the outer cylinder of 46,200 cycles.

Brake and Anti-Skid

The Brake Control Unit (BCU), two Dual Brake Control Valves (DBCV), two Anti-Skid Manifolds (ASM), two Dual Wheelspeed Transducers (WST), and two Single WST's were removed from the accident airplane and shipped to their respective manufacturers for testing under the supervision of the airworthiness group. The testing involved two phases; the Phase 1 objective was to measure the characteristics and stability of the brake pressure output from the DBCV's in response to brake pedal inputs with no anti-skid control while the Phase 2 objective was to investigate the stability of the anti-skid control system during a simulation of the accident landing and examine the effect of brake torque and cooling of the brake fluid on the stability of the system.

The DBCV's were installed in a hydraulic simulator to test the brake pressure output in relation to a specified input. The first part of the test involved manual actuation of the DBCV slowly to full travel and release back to zero while recording the input arm angle versus output pressure. The tests on both DBCV's were performed with the accident airplane anti-skid manifold. The input angle was measured with a potentiometer on the actuation lever and the brake pressure was measured at the brake for each of the four inputs from the anti-skid manifold. The input pressure to the ASM was also measured for comparison. For both valves the anti-skid manifold was installed but no anti-skid control was provided.

During multiple tests, a reasonably consistent effect was seen. As the input angle increased from zero, there was no response from the valves until about 11 to 13 degrees when the brakes exhibited a step response up to about the input pressure level. As the DBCV was actuated to its full travel and back to zero the response from all four brakes was smooth and matched the input pressure in slope.

The second phase of testing on the DBCV's involved rapid manual activation of the valves such that the output pressure was about 1/4, 1/2, 3/4, and full system pressure while measuring the pressure recorded at the four brakes as a function of time. In all of the results there was an initial lag between the DBCV output pressure and the response measured at the brakes, and some notable oscillation.

When examining the right side DBCV, there was some contamination noted inside the left second stage sensing assembly and some moderate to heavy scratching/scoring on the plunger.

In parallel to the investigation and in response to flight crew reports, FedEx began bleeding the brakes on all of their MD-10-10F airplanes and examining the fluid taken from the brake systems of these airplanes. Many fluid samples had contamination levels well above the recommended limits. Several brake system components from other FedEx airplanes exhibited a range of contamination damage from light to severe.

ORGANIZATIONAL AND MANAGEMENT INFORMATION

FedEx was incorporated in June 1971 and, in April 1973, began operating 14 corporate-type jet airplanes from the airline's hub at MEM. After the deregulation of the air cargo industry in 1977, FedEx began to expand, acquiring more and larger airplanes (including Boeing 727s and McDonnell Douglas DC-10s) and using multiple airports for its operations. In recent years, FedEx has added various models of Boeing, Airbus, Fokker, ATR, and Cessna airplanes to its fleet, including Boeing/McDonnell Douglas MD-11s/-10s and Airbus A300s and A310s. At the time of the accident, FedEx operated a fleet of 624 airplanes with about 4,200 pilots.

ADDITIONAL INFORMATION

Previous Gear Collapse Event

On December 18, 2003, a Fedex MD-10-10F crashed while landing at Memphis International Airport (MEM), Memphis, Tennessee. The right main landing gear collapsed after touchdown on runway 36R, and the airplane veered off the right side of the runway. After the gear collapsed, a fire developed on the right side of the airplane. (NTSB #DCA04MA011, AAR/05/01). The fracture of the right main landing gear of this airplane initiated from the same air filler valve bore hole location as N391FE, however the investigation concluded that the "excessive vertical and lateral forces on the right main landing gear during the landing exceeded those that the gear was designed to withstand and resulted in the fracture of the outer cylinder and the collapse of the right main landing gear."

Air Filler Valve Bore Inspection

As a result of preliminary investigation findings, Boeing issued Alert Service Bulletin DC10-32A259 on October 30, 2007. The Bulletin instructed the operator to perform an inspection of the MLG shock strut cylinder air filler valve bore for the presence of stray nickel or chrome plating deposits, corrosion, or cracks. If any of these conditions were found, the service bulletin provided instructions for repair or replacement of the MLG shock strut cylinder assembly. Prior to the release of the Service Bulletin, Boeing issued a revision to the Component Maintenance Manual (CMM) Chapter 32-11-01 on September 15, 2007. The revision added instructions for a video probe inspection of the air filler valve bore for corrosion, sulfamate nickel or chrome plating splatter, tool marks, or other defects followed by an eddy current inspection of the bore for cracks. Instructions for repair of allowable damage were also included. Several Temporary Revisions to CMM 32-11-04 were also issued to add instructions for inspection and repair of the air filler valve bore.

On May 2, 2008 the FAA issued AD 2008-09-17 requiring that operators perform a video scope inspection of the air filler valve bore for the presence of stray nickel or chrome plating deposits and requiring them to perform the investigative and corrective actions per the Boeing Alert Service Bulletin. The AD became effective on June 6, 2008. The required inspections and corrective actions must be performed within 24 months for all passenger airplanes and those freighter airplanes with cylinders having less than 7,200 flight cycles flown in the freighter configuration. They must be performed within 6 months for those freighter airplanes with cylinders that have accumulated more than 7,200 flight cycles in the freighter configuration.

Brake and Antiskid Modifications

The investigation found that some of the 15 FedEx MD-10 airplanes (including the accident airplane) with the carbon brake system installed had occasional pilot reports of unacceptable brake grabbing, aircraft pulling left or right during braking, excessive pedal travel to obtain braking, and aircraft shuddering (shaking) during braking. The pilot reports were causing costly delays and unproductive maintenance.

ISE data and information from the accident investigation led to three likely causes for the pilot reports.

1) With small brake pedal(s) applications typical in normal landing and taxi operations, the time between initial brake pedal motion and the start of brake torque can be longer than expected. This delay frequently causes the flight crew to further advance the brake pedals, which results in a high initial brake pressure and torque. The high initial brake torque could be perceived as "brake grabbing" by the flight crew. The delayed brake response is due to a combination of factors that slow the hydraulic fill and stroke of the brake pistons necessary to engage the rotating and stationary disks in each brake. The carbon brakes have 40% larger piston displacements than the original steel brakes. This delayed response of the brakes can also be seen with the DBCV's and ASM's from the accident airplane.

2) After initiation of braking torque, the antiskid control software can command a near simultaneous pressure reduction in multiple brakes on one or both MLG. The resulting brake torque can then be reduced to near zero for a short period, interrupting the airplane deceleration braking force from one or both MLG, causing directional pulling and/or allowing the MLG to oscillate fore & aft. The pressure reduction occurs due to the antiskid initialization feature in the ASCU that is designed to quickly optimize brake pressures at the start of a rejected takeoff. The difference in the time of reduction in brake inlet pressures can result in pilot reports of aircraft pulling left or right during braking and aircraft shuddering during braking.

3) Hydraulic fluid contamination can result in internal damage and malfunction of brake system components. These malfunctions can increase the time to fill the brakes, and in some instances, block the flow of hydraulic fluid to a brake and/or interfere with the satisfactory operation of the antiskid function. Evidence of brake fluid contamination was found on components from the accident airplane and other FedEx MD-10-10F airplanes.

As a result of the data obtained from the ISE, the information uncovered during the accident investigation, and continued support from FedEx, several changes were made to the MD-10 carbon brake system to improve its performance. All of these improvements were installed first on N357FE, the ISE airplane, to substantiate their performance prior to installing them on the rest of the carbon brake equipped MD-10 aircraft.

To assure clean hydraulic fluid on the 14 FedEx aircraft with the carbon brake system, two main modifications were performed. First, the antiskid manifold return line filters were removed in order to assure any debris in the brake system would flow to the hydraulic system reservoirs and the aircraft hydraulic system filters rather than remain in the ASM. Second, the brakes were replaced and the brake hydraulic systems were flushed to assure the removal of any contamination currently in the system.

The DBCV was modified to reduce both the initial dead band and the pressure gain versus the brake pedal position. The modified schedule starts metered pressure output at a lower lever position (reduced dead band) and meters a lower pressure output for the first half of the lever travel. This modification reduces the delay between initial brake pedal advance and initial brake torque. In addition, other minor changes to the DBCV increased the fluid flow at small lever positions.

The ASM was modified to change the brake inlet pressure response characteristic versus control signal from the ASCU and a separate 3000 psi hydraulic source was added to the brake system #2 ASM on each MLG. During brake pedal application typical in normal landing and taxi operations, the modified brake inlet pressure schedule ("unigain") prevents any momentary pressure reduction commanded by the ASCU in one-half of each MLG brake (4 of 8 pistons). The modification does not affect brake system operation for brake pedal applications of more than about three-fourths of full travel. The modification eliminates the initialization software effect to brake system #2 preventing the pressure reduction at all wheels on each MLG. The brake torque reduction is changed from almost 100% to about 50% preventing the oscillations of the MLG seen in the ISE data.

Testing of the modifications after installation on the ISE airplane, N357FE, indicated that the MLG 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 reduction in multiple brake pressures, and minimal fore/aft movement of the main gears during braking. These two brake system improvements, along with the modified brake system described earlier, were being installed on all MD-10-10F and MD-10-30F aircraft.

Pilot Information

Certificate:	Airline Transport	**Age:**	, Female
Airplane Rating(s):	Multi-engine Land; Single-engine Land	**Seat Occupied:**	Left
Other Aircraft Rating(s):		**Restraint Used:**	Seatbelt, Shoulder harness
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	Airplane Multi-engine; Airplane Single-engine; Instrument Airplane	**Toxicology Performed:**	Yes
Medical Certification:	Class 1 Without Waivers/Limitations	**Last Medical Exam:**	07/19/2006
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	07/19/2006
Flight Time:	11262 hours (Total, all aircraft), 4402 hours (Total, this make and model), 9522 hours (Pilot In Command, all aircraft)		

Co-Pilot Information

Certificate:	Airline Transport; Flight Engineer	**Age:**	
Airplane Rating(s):	Multi-engine Land; Single-engine Land	**Seat Occupied:**	Right
Other Aircraft Rating(s):		**Restraint Used:**	Seatbelt, Shoulder harness
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	None	**Toxicology Performed:**	Yes
Medical Certification:	Class 1 Unknown	**Last Medical Exam:**	03/01/2006
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	06/20/2006
Flight Time:	854 hours (Total, all aircraft), 244 hours (Total, this make and model)		

Aircraft and Owner/Operator Information

Aircraft Manufacturer:	BOEING	**Registration:**	N391FE
Model/Series:	MD-10-10F	**Aircraft Category:**	Airplane
Year of Manufacture:		**Amateur Built:**	No
Airworthiness Certificate:	Transport	**Serial Number:**	46625
Landing Gear Type:	Retractable - Tricycle	**Seats:**	3
Date/Type of Last Inspection:	07/28/2006, AAIP	**Certified Max Gross Wt.:**	443000 lbs
Time Since Last Inspection:		**Engines:**	3 Turbo Fan
Airframe Total Time:	73283 Hours	**Engine Manufacturer:**	General Electric
ELT:	Installed, not activated	**Engine Model/Series:**	CF-6
Registered Owner:	Federal Express Corp.	**Rated Power:**	
Operator:	FEDERAL EXPRESS CORP	**Air Carrier Operating Certificate:**	Flag carrier (121)
Operator Does Business As:		**Operator Designator Code:**	FDEA

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual Conditions	**Condition of Light:**	Day
Observation Facility, Elevation:	MEM, 341 ft msl	**Observation Time:**	1630 UTC
Distance from Accident Site:		**Direction from Accident Site:**	
Lowest Cloud Condition:	Few / 7500 ft agl	**Temperature/Dew Point:**	26°C / 18°C
Lowest Ceiling:	Overcast / 15000 ft agl	**Visibility**	10 Miles
Wind Speed/Gusts, Direction:	14 knots/ 18 knots, 270°	**Visibility (RVR):**	
Altimeter Setting:	30.15 inches Hg	**Visibility (RVV):**	
Precipitation and Obscuration:			
Departure Point:	SEATTLE, WA (SEA)	**Type of Flight Plan Filed:**	IFR
Destination:	Memphis, TN (KMEM)	**Type of Clearance:**	IFR
Departure Time:	1257 UTC	**Type of Airspace:**	

Airport Information

Airport:	Memphis International (KMEM)	**Runway Surface Type:**	Asphalt
Airport Elevation:	341 ft	**Runway Surface Condition:**	Dry
Runway Used:	18R	**IFR Approach:**	ILS
Runway Length/Width:	9329 ft / 150 ft	**VFR Approach/Landing:**	Straight-in

Wreckage and Impact Information

Crew Injuries:	3 None	**Aircraft Damage:**	Substantial
Passenger Injuries:	N/A	**Aircraft Fire:**	On-Ground
Ground Injuries:	N/A	**Aircraft Explosion:**	None
Total Injuries:	3 None	**Latitude, Longitude:**	

Administrative Information

Investigator In Charge (IIC):	William R English	**Adopted Date:**	12/30/2008
Additional Participating Persons:	Victoria E Anderson; FAA		
Publish Date:	07/10/2009		
Investigation Docket:	NTSB accident and incident dockets serve as permanent archival information for the NTSB's investigations. Dockets released prior to June 1, 2009 are publicly available from the NTSB's Record Management Division at pubinq@ntsb.gov, or at 800-877-6799. Dockets released after this date are available at http://dms.ntsb.gov/pubdms/.		