AIRCRAFT ACCIDENT REPORT 4/2003

Air Accidents Investigation Branch

Department for Transport

Report on the accident to McDonnell-Douglas MD-83, EC-FXI at Liverpool Airport on 10 May 2001

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This investigation was carried out in accordance with
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Department for Transport

Air Accidents Investigation Branch

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October 2003

The Right Honourable Alastair Darling
Secretary of State for Transport

Dear Secretary of State

I have the honour to submit the report by Mr P D Gilmartin, an Inspector of Air Accidents, on the circumstances of the accident to McDonnell-Douglas MD-83, EC-FXI, which occurred at Liverpool Airport on 10 May 2001.

Yours sincerely

Ken Smart
Chief Inspector of Air Accidents

Contents **Page**

5 Appendices

Appendix A	EC-FXI Flight Recorder Data
Appendix B	MD-80 Series main landing gear oleo strut
Appendix C	'As found' picture of upper half of fractured MLG cylinder showing the major fatigue crack
Appendix D	Scanning electron microscope secondary image of major fatigue crack Scanning electron microscope backscatter image of major fatigue crack
Appendix E	SEM photograph of the surface finish of the failed cylinder from G-DEVR SEM photograph of the surface finish of the failed cylinder from EC-FXI

GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB	-	Air Accidents Investigation Branch
AAR	-	Aircraft Accident Report (AAIB)
ABS	-	Aircraft Braking Systems
ACC	-	Area Control Centre (ATC)
AD	-	Airworthiness Directive
AFS	-	Airport Fire Service
agl	-	Above ground level
AMS	-	Aircraft Material Specification
ASB	-	Alert Service Bulletin
ATC	-	Air Traffic Control
ATIS	-	Automated Terminal Information Service
BCA	-	Boeing Commercial Airlines
CAA	-	Civil Aviation Authority
CSN	-	cycles since new
CVR	-	Cockpit Voice Recorder
DAC	-	Douglas Aircraft Corporation
DOT	-	Department of Transportation (USA)
DMS	-	Douglas Material Specification
DPS	-	Douglas Process Specification
DV	-	Direct vision
FAA	-	Federal Aviation Administration (USA)
FAR	-	Federal Aviation Regulation(s)
FDAU	-	Flight Data Acquisition Unit
FDR	-	Flight Data Recorder
FL	-	Flight Level
FO	-	First Officer
g	-	gravitational acceleration
G/S	-	glideslope
HV	-	Hardness - Vickers
ILS	-	Instrument Landing System
kg	-	kilogram(s)
km	-	kilometre(s)
ksi	-	thousands of pounds (force) per square inch
kt	-	knot(s)
JAR	-	Joint Aviation Requirements
LOC	-	Localiser (ILS)
LW	-	Landing Weight
mb	-	millibars (pressure)
MD	-	McDonnell-Douglas
METAR	-	Meteorological Aerodrome Report
MHz	-	Megahertz
MLG	-	Main Landing Gear
mm	-	millimetre(s)
MPa	-	Mega Pascals
MPI	-	Magnetic particle inspection
NDE	-	Non destructive examination
nm	-	nautical mile(s)
QFE	-	pressure setting to indicate height above aerodrome
OPS	-	Operations
QNH	-	Corrected mean sea level pressure
RFF	-	Rescue and Fire Fighting
RH	-	Radio height
SB	-	Service Bulletin
SOP	-	Standard Operating Procedure(s)
SU	-	spin up (wheel)
TAF	-	Terminal Area Forecast
TDO	-	Transient drag oscillation
TOM	-	Take-off mass
TRK	-	Track
UK	-	United Kingdom
USA	-	United States of America
UTC	-	Coordinated Universal Time
V_{REF}	-	Reference threshold speed
°T, °M	-	degrees True, Magnetic
°C	-	degrees Celsius

Air Accidents Investigation Branch

Aircraft Accident Report No: 4/2003 (EW/C2001/5/1)

Registered Owner and Operator:	Spanair
Aircraft Type:	McDonnell Douglas (Boeing) MD-83
Nationality:	Spanish
Registration:	EC-FXI
Place of accident:	Liverpool Airport Latitude: 53° 20'N Longitude: 002° 51'W
Date and Time:	10 May 2001 at 1232 hrs (all times in this report are UTC)

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) by the Air Traffic Control (ATC) Watch Manager at Liverpool Airport. The investigation was conducted by: Mr D King (Investigator-in-Charge), Miss G M Dean (Operations), Mr S W Moss (Engineering) and Mr R James (Flight Recorders). During the course of the investigation, Mr P D Gilmartin was appointed to replace Mr King as Investigator-in-Charge.

The aircraft carried out an automatic landing at Liverpool at 1232 hrs with the first officer (FO) being the pilot flying. The right main landing gear collapsed on touchdown and the commander took over control shortly afterwards. The aircraft continued travelling along the runway, maintaining approximately the centreline, and came to rest with the right wing in contact with the ground. A successful passenger evacuation was carried out using the forward escape slides and the left overwing emergency exit.

The following causal factors were identified:

1 The right Main Landing Gear (MLG) cylinder failed immediately upon touchdown due to the application of spin-up drag loads on a section of the cylinder containing a major fatigue crack 3.2 mm long and 1.0 mm deep and several other associated smaller cracks.

2 The origins of these fatigue cracks could not be identified but other embryonic cracks were found which were associated with surface irregularities arising from a grit-blasting process during manufacture. Abnormal loading, possibly due to an occurrence of a mode of fore-and-aft vibration known as ‘gear walking’ is thought to have been responsible, at some time in the aircraft’s history, for propagating the cracks to a depth at which continued growth was possible under normal loading. Alternatively, some abnormal loading may have relaxed the beneficial compressive surface stresses induced by shot-peening at the critical section and allowed propagation from the same surface defects.

3 Inspection and other mandatory preventive measures taken following two similar accidents did not prevent the occurrence of this third accident. This was probably due to the small size of cracks which are required to be detected before reaching a critical dimension.

Five safety recommendations have been made.

1 Factual Information

1.1 History of the flight

The aircraft was engaged on a holiday charter flight from Palma de Mallorca, Spain, to Liverpool Airport. The following history of flight was compiled from information recorded by the Flight Data Recorder (FDR), the Cockpit Voice Recorder (CVR), Air Traffic Control (ATC) radar and voice recordings, and from interviews with the flight crew.

1.1.1 Descent

The first officer was the handling pilot for the approach and subsequent landing at Liverpool. Having been in the cruise at FL350 at Mach 0.75, the aircraft was given a radar heading of 350°M and was cleared to descend to FL290. The commander obtained the Liverpool ATIS, coded 'Uniform', recorded at 1203 hrs which indicated: 'RUNWAY 09, SURFACE WIND VARIABLE 2 KT, VISIBILITY 15 KM, CLOUD FEW AT 4,000 FEET, TEMPERATURE +18°C, DEWPOINT +13°C, QNH 1019, QFE 1017, RUNWAY DAMP, DAMP, DAMP.'

Further descent was given and the aircraft was handed over to Manchester Area Control Centre (ACC) on frequency 124.20 MHz. Manchester ACC cleared further progressive descent to FL80 and gave radar vectors to turn left onto 270°M before handing over to a second frequency, 128.05 MHz. The commander, having reported his speed and heading, received clearance to descend to FL60. He then asked ATC if it was possible to perform a Category II ILS approach to Runway 27 for training purposes. ATC advised that they would pass the request onto Liverpool ATC.

The aircraft was given further radar vectors, to a position initially to the north of Liverpool Airport and descent clearance down to 3,500 feet on the QNH of 1019 mb, before the aircraft was handed over to Liverpool Approach Control on 119.85 MHz. The crew were also instructed to repeat their request for Runway 27 upon making contact. At the time of the handover, the aircraft was descending through 6,100 feet at 256 kt and on a heading of 310°M.

1.1.2 Approach

The Liverpool Approach controller acknowledged the training request and advised that the crew would be given radar vectors for a right hand circuit to the ILS on Runway 27, for a practice Category II ILS, with no low visibility ILS protection. While descending through 3,700 feet at 270 kt, the aircraft began a right turn onto 360°M and, one minute later, levelled at 2,500 feet in accordance with the ATC instructions. The aircraft flew level at this altitude for a period of three and a half minutes during which time airspeed was reduced to, and maintained, at 210 kt. Further progressive heading changes were given by ATC onto 105°M. As the aircraft turned onto this heading, still maintaining 210 kt, it was cleared to descend to 1,800 feet with '20 TRACK MILES TO TOUCHDOWN'.

Once level at this new altitude, the Liverpool Approach controller instructed a right turn heading 130° towards base leg. This was followed 30 seconds later by a further 'TURN RIGHT, HEADING 180 BASE GIVING 10 TRACK TO TOUCHDOWN' at that point. The aircraft was turning right through 144°M towards the new heading when ATC requested a further turn onto 240° to close the localizer from the right and report established. Still maintaining 1,800 feet at 210 kt and turning right through 220°M, the aircraft passed through the runway extended centreline and reached a maximum recorded localizer deflection of three dots to the left of the required inbound track. The right turn was continued until the aircraft achieved a heading of 290°M. The aircraft had begun to regain the extended centreline as ATC advised the crew that their range was now six miles and gave descent instructions to descend to 1,500 feet.

Flap 10° was selected and the Autoland system was armed. Medium Autobrake was selected for the landing. The final descent commenced with glideslope capture from five nm. The thrust levers were retarded to idle and airspeed started to reduce from 213 kt. The landing gear was lowered while speed was reducing through 210 kt resulting in a single 'LANDING GEAR' audio warning. ATC advised the crew of a light aircraft that had just become airborne from Runway 09 and then advised them to continue with the Cat II approach before handing them over to Liverpool Tower on frequency 126.35 MHz.

1.1.3 Landing

With the airspeed reducing through 200 kt, while descending through 920 feet agl, the crew selected Flap 40° and advised the Liverpool Tower controller that they were at a range of two miles on final approach. The landing clearance was issued with a surface wind check of 070° at 13 kt. At 550 feet agl, as the flaps reached full extension, the recorded Autopilot mode changed to 'AUTOLAND'. At 500 feet Radio Altitude, the FDR recorded an airspeed of 176 kt.

During the remaining 34 seconds of flight, airspeed reduced continuously from 176 kt to a recorded value of 136 kt at touchdown. Also, during this period, the recording of glideslope deviation indicated that the flightpath of the aircraft was marginally steeper than the specified 3° glidepath angle.

The sequence of the various modes of the Autopilot during the Autoland were recorded as operating correctly and the aircraft touched down approximately on the runway centreline at a pitch attitude of 3.7° nose up and a roll attitude of

2.6° right wing down. The recordings of normal acceleration and lateral acceleration at touchdown showed maximum values of 1.56 'g' and 0.1 'g' respectively. Immediately upon touchdown the right main gear discrete parameter indicated that the gear had come out of the downlock position and aural warnings of 'LANDING GEAR' were recorded on the CVR until power was eventually removed. The FDR indicated that there was no pressure applied to either the left or right braking system prior to, or during, the touchdown.

1.1.4 Deceleration

During the three seconds after touchdown, the roll attitude increased to 10.5° right wing down. The Autopilot disengaged and, from this point for a further 23 seconds, aural warnings of 'AUTOPILOT' were recorded on the CVR, alternating with the 'LANDING GEAR' warnings. Ground spoiler deployment was not a parameter recorded on the FDR but the left outboard flight spoiler moved to maximum deflection within 1.5 seconds of the touchdown, consistent with ground spoiler operation. The right inboard flight spoiler would also have indicated maximum deflection, but as the aircraft rolled to the right following the touchdown, up to 10° of left aileron control input was applied, which reduced the amount that the right spoilers extended. One second after the Autopilot disconnected, the aircraft began to yaw to the left and progressively more right rudder was applied. Manual braking was commenced at the same point (127 kt) with twice as much deflection of the right brake pedal as that of the left. Roll attitude fluctuated between 6° and 11.8° right wing down.

The flight crew became aware of a lurch to the right a few seconds after touchdown. Control of the aircraft was passed to the commander who manually applied the brakes and attempted to keep the aircraft running straight along the centreline. Recorded Localizer deviation indicated that the aircraft, although yawing left, remained essentially on the runway centreline. As the airspeed reduced through 124 kt, reverse thrust on both engines was applied. By 114 kt, both thrust reversers had deployed fully and the aircraft had yawed 8° left of runway heading. Roll attitude began to stabilise at 10.9° right wing down.

Three seconds later, as the aircraft decelerated through 102 kt, maximum right rudder (27°) and right brake pedal deflection (17.8°) values were recorded. At the same time, left brake pedal deflections of approximately 9° were observed as the aircraft began to yaw right again towards runway heading.

Decelerating through 68 kt, with the aircraft heading straight, the rudder was neutralised although there was no change in the brake pedal deflections. Reverse thrust was cancelled at 63 kt and the aircraft continued to decelerate under manual braking. The 'AUTOPILOT' aural warning was cancelled as the airspeed reduced through 35 kt and the aircraft eventually came to rest twelve seconds later, close to the runway centreline with a roll attitude of 12.1° right wing down. A graph of pertinent parameters recorded during the approach and landing phase of the accident flight are shown in Appendix A.

External witnesses to the landing described seeing a puff of smoke from the tyres and hearing a bang at the time of touchdown. This was immediately followed by the aircraft “dropping” to the right.

After the aircraft had come to rest, the commander reported to ATC that they had a problem with the right tyre. ATC responded that the fire service was on the way. Meanwhile the first officer opened and looked out of the direct vision (DV) window on the right side. She advised the commander that the right wing was on the ground. He announced an emergency evacuation to the crew and the passengers. The Liverpool Tower controller advised the crew about the availability of the Airport Fire Service (AFS) frequency of 121.6 MHz, however no communication was made on this frequency.

The cabin crew opened the two forward emergency exit doors and all but one of the passengers exited the aircraft using one of the two forward escape slides. A single passenger opened and evacuated through the left side overwing escape exit.

At 1232 hrs, immediately after the aircraft had touched down, the Tower controller pressed the crash alarm. The AFS deployed and arrived at the site within the required two minute response time. Although there was no apparent fuel spillage, there was evidence of some fluid leakage. Two fire vehicles laid a foam blanket around the right wing area and further fire crew members assisted passengers who were evacuating from the forward slides. Once informed that all passengers were off the aircraft, the Station Officer sent a team on board to check through the aircraft and confirm that it was empty.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	-	-	-
Serious	-	-	-
Minor/none	6	45	-

1.3 Damage to aircraft

The right MLG leg had fractured with consequent damage to MLG components, MLG door and right inboard flap. There was abrasion damage to the right wing slats, flaps and wing tip.

1.4 Other damage

Minor damage to runway surface.

1.5 Personnel information

1.5.1 Commander: Male, aged 32 years

Licence:	Airline Transport Pilot's Licence		
Aircraft ratings:	MD-83		
Licence Proficiency Check:	11 January 2001		
Annual line check:	11 January 2001		
Medical certificate:	Class 1 issued 15 February 2001		
Flying experience:	Total all types:	5,037 hours	
	Total on type:	4,061 hours	
	Total last 28 days:	83 hours	
	Total last 24 hours:	5 hours	

1.5.2 First officer: Female, aged 28 years

Licence:	Airline Transport Pilot's Licence	
Aircraft ratings:	MD-83	
Licence Proficiency Check:	23 December 2000	
Annual line check:	23 February 2001	
Medical certificate:	Class 1 issued 7 December 2000	
Flying experience:	Total all types:	2,132 hours
	Total on type:	1,624 hours
	Total last 28 days:	31 hours
	Total last 24 hours:	5 hours

1.5.3 Flight crew duty time:

Previous rest period:	Off duty:	2015 hrs on 8 May 2001
	On duty:	0405 hrs on 10 May 2001
	Total rest	31 hrs 50 mins
Available flight duty period		12 hours

The flight crew reported for duty at 0405 hrs 10 May 2001 for a planned four sector duty day, of which the accident flight was the third sector. At the time of the accident, the crew had completed a flight duty period of 8 hours and 27 minutes.

1.5.4 Crew reports

A post accident interview with the flight crew was conducted during the day following the accident. The flight crew were reluctant to assist the investigation at this stage having stated a preference for supplying information only when some days had passed. The co-operation achieved from the flight crew was poor; there was a reluctance to supply pertinent, timely, information and thereby to further the progress of the investigation. During the interview they both described the flight, approach and landing as having been normal until a few seconds after touchdown. They also observed that neither of them heard any aircraft generated warnings or cautions at any time.

The cabin crew, who co-operated readily with the investigation, described the landing as "firm" but reported that they did not notice anything unusual during the landing roll except for a strong smell of burning rubber. Once the aircraft had come to rest they became aware of an unusual roll attitude.

1.6 Aircraft information

1.6.1 Leading Particulars

The MD-80 series of aircraft are cantilever low wing monoplane, short/medium range airliners powered by two Pratt and Whitney JT8D series engines, one mounted either side of the rear fuselage. The MD-83 has a wing span of 32.87 metres and an overall length of 45.06 metres. The manufacturer's serial number of EC-FXI was 49630 and it was delivered new in 1989. At the time of the accident it had accumulated a total of 42,293 flying hours and 21,327 landings.

1.6.2 Aircraft data

Actual Take off mass (TOM)	136,272 lb (61,812 kg)
Maximum TOM	160,000 lb (72,575 kg)
Actual Zero fuel weight (ZFW)	94,772 lb (42,988 kg)
Maximum ZFW	122,000 lb (55,338 kg)
Fuel on landing	25,500 lb (11,566 kg)
Actual Landing weight (LW)	120,272 lb (54,554 kg)
Maximum LW	139,500 lb (63,276 kg)
V_{REF} 40° flap	128 kt

The aircraft was in an all economy class, 170 passenger seat configuration, with a single aisle. There are eight emergency exits on the type; one pair of Type I exits in the forward fuselage, two pairs of Type III exits overwing, two further Type I exits, one on the left side of the rear fuselage and one at the rear of the cabin.

1.6.3 Development of the MD-80 series of aircraft

The Douglas Aircraft Corporation (DAC) (later known as McDonnell-Douglas) DC-9 type first entered service in 1965. Progressive product development continued to produce ‘stretched’ versions of the aircraft with greater capacity. With a further elongation of the fuselage and the introduction of a different type of engine, the type was renamed to the MD-80 series of aircraft from 1979 onwards. During 1997, McDonnell-Douglas merged with Boeing and responsibility for production and support of McDonnell-Douglas commercial aircraft was transferred to Boeing Commercial Airplanes (BCA).

As a result, the MD-80 series share many common components with the earlier DC-9 models. In general, however, they have higher capacity and higher operating weights than the DC-9. In particular, this necessitated a stronger landing gear, this being achieved by some dimensional changes and a change of material from the original ‘Hy-Tuf’ (specification AMS 6418) to Ultra-High Tensile 300M steel produced to Douglas Material Specification (DMS) 1935/MIL-S-8844.

1.6.4 Description of the Landing Gear

1.6.4.1 General

The MD-80 MLG is of conventional configuration, retracting inboard (Appendix B). Suspension and damping are achieved by an oleo-pneumatic piston operating in a cylinder, with torsional motion being prevented by a torque link incorporating a shimmy-damper. The cylinder, including the trunnions, is a single forging of 300M ultra-high tensile steel, as is the piston which incorporates the axle.

The MD-80 MLGs were designed by the DAC, but sub-contracted out for manufacture. They were originally produced by Cleveland Pneumatic (now B F Goodrich), but in 1989 production switched to Menasco Aerospace of Ontario, Canada. Both manufacturers worked to the same drawings and the landing gears are interchangeable, both as complete units and at the individual component level.

The component which failed on EC-FXI was the right-hand MLG cylinder. After forging, the cylinders are heat-treated and machined to the drawing dimensions. They are then externally shot-peened to Douglas Process Specification DPS 4.999, following which they are blasted with aluminium oxide grit to prepare the surface for cadmium plating. After plating is completed, the surface is primed and painted with an impact-resistant paint. The foregoing description is only a brief summary of the most significant of the many processes involved in the manufacture of the cylinder, a highly-loaded precision component.

In order to comply with internationally accepted Federal Airworthiness Regulations relating to crashworthiness, a section of the cylinder was designed to be 'fusible', so that the leg would fail first at this location, assuming that the overload was to occur in an aft-and-upward direction. This should result in a 'clean' detachment of the leg, in a heavy landing or over-run situation, without rupturing the integral wing fuel tanks. This 'critical' cross section occurred immediately below a reduction in cylinder wall thickness approximately 18 inches below the centreline of the landing gear mounting trunnion. Although this was effectively a 'weak point' on the leg, it was considered by DAC that it met the normal stress requirements, albeit marginally, and that its stress Reserve Factor was necessarily close to unity. (See paragraph 1.16.2.)

The braking system is of the traditional type, with an electronically controlled anti-skid system modulating conventional hydraulic brakes with discs of steel construction. Signals from each mainwheel speed transducer are input to the Anti-skid Control Unit, which outputs a signal to the associated Anti-skid Control Valve, causing a removal of hydraulic pressure to the relevant brake unit if an impending skid is sensed. As the wheel accelerates again, the pressure is re-applied at a lower value until a further impending skid is sensed, when it is again released. This is repeated until, assuming a constant pilot's pedal pressure and a constant runway friction coefficient, the brake pressure settles down at a value just optimised for maximum braking effort without causing a skid.

1.6.4.2 Main Landing 'Gear Walking'

'Gear walking' is a term used to describe a mode of MLG self-sustaining vibration. It is primarily due to a dynamic coupling of the anti-skid modulation frequency with the natural fore-and-aft response frequency of the MLG leg and can be additionally affected by such factors as tyre pressures and the presence of air in the brake system hydraulics. On the application of sufficient brake pressure, the MLG legs flex rearwards and when an incipient skid is detected by the anti-skid system the brake pressure is released. On brake release, the leg 'springs' forward, rapidly accelerating the wheel which signals the anti-skid system to re-apply the brakes. On brake re-application the leg again flexes rearwards and so on.

BCA advised that their investigation into 'gear walking' indicated that it only occurred with anti-skid valves whose gains were on the high side of the normal distribution of acceptable gains.

1.6.4.3 Fatigue life calculations for the Main Landing Gear

During development of the DC-9 aircraft, strain gauge and full-scale fatigue tests were carried out on the landing gears. With the advent of the MD-80 no such testing was done and verification of the loading and fatigue life of the MLG was achieved by calculation and extrapolation of the data from the DC-9 tests. Fatigue and fracture toughness information for 300M material was taken from the material specification and from DAC's own testing data. The test regime employed used un-peened material, as it was felt that any benefit shot-peening might bring to the fatigue life should be considered a 'bonus' to the fatigue life calculations.

The fatigue calculations involved devising a spectrum of 'typical' mission profiles with taxi, takeoff and landing loads calculated for various assumed aircraft weights and variation of pilot technique (heavy/moderate braking, normal/firm/heavy landings etc). An assumed number of occurrences for each mission profile was included in the total spectrum for the aircraft's life, together with various known transient or oscillatory loading modes. Principal stresses calculated for each case were factored using a figure of stress concentration (K_1) to take into account changes in material cross-section occurring at the various critical points being considered.

For the landing and braked roll case for the cylinder, the calculations centred on the 'critical' section, mentioned in paragraph 1.6.4.1 above, in recognition that the stresses would be highest at this point. The data showed that, in terms of fore-and-aft stresses on the cylinder, only three cases produced stress values sufficient to cause fatigue damage. These were particular wheel spin-up (SU) and spring-back loads, and a fore-and-aft transient drag oscillation (TDO) occurring on touchdown. Although one of the SU stresses was high, in the order of 220 ksi (thousands of pounds per square inch), this was for a heavy landing case, of which only some 12 events were forecast in the typical life of the landing gear. Thus, in terms of fatigue propagation, it amounted to a small amount of damage, because the number of stress cycles was so low. In the other two spring-back and TDO cases, the stresses were much lower (in the order of 150 ksi), but there were a larger number of cycles for a given number of flights.

Based on a maximum expected component life of 150,000 flights, the above calculations gave a safe life limit of 12 million cycles, which was therefore effectively unlimited.

1.6.4.4 Previous cases of MLG cylinder failure

On 27 April 1995, an MD-83 aircraft, registration G-DEVR, experienced failure of a left MLG cylinder whilst landing at Manchester International Airport, UK. Full details of this accident are contained in Aircraft Accident Report (AAR) No 1/97. Whilst this failure bore many similarities with the accident to EC-FXI, it should be noted that it occurred at relatively low speed while braking during the landing roll.

An accident in almost identical circumstances to G-DEVR occurred to an MD-82 registration B-2135 at Jinan airport, China on 27 April 1997. It is not known whether an official report is available into this accident, but information was supplied by BCA, who had participated in the investigation. The fatigue crack in this case was in the same place and of an almost identical size to that on G-DEVR and the cylinder had been inspected in accordance with Service Bulletin (SB) MD80-32A286 (see paragraph 1.6.4.5) only some 482 landings prior to failure with no cracks having been detected.

1.6.4.5 Previous modification and inspection requirements

In the following paragraphs, all SB numbers, which using the full nomenclature should strictly include the prefix MD80-, are referred to in an abbreviated form. (ie SB MD80-32-246 is written SB 32-246)

Prior to the accident to G-DEVR, there were no specific inspections for cracks required of MD-80 MLG cylinders beyond the routine ones performed at MLG overhaul. Until the issue of SB 32-246 (see below), restrictors in the brake hydraulic lines were not fitted.

SB 32-246, which fitted hydraulic brake line restrictors to aircraft equipped with an ABS (Loral) braking system, had been issued in 1991, with a 'recommended' compliance. In March 1995, a further SB, No 32-276, was issued which fitted restrictors to Bendix braking system-equipped aircraft. In addition, since these restrictors incorporated filters which were not a feature of those embodied under SB 32-246, the SB also called for replacement of the earlier design of restrictor on aircraft previously modified 'at the earliest practical maintenance period not to exceed four years from receipt of SB 32-276'. For aircraft which had not had any restrictors fitted, (which included EC-FXI) a compliance time of two years was recommended. This timescale was revised in an October 1995 revision to 12 months.

Although timescales were specified in both the above mentioned Service Bulletins, compliance remained as 'recommended' until after the G-DEVR accident, when the FAA issued Airworthiness Directive (AD) 96-01-09, with an effective date of February 1996, which mandated fitment of restrictors to SB 32-276 on all aircraft not previously modified to either SB 32-246 or 32-276 within nine months. It did not, however, call for replacement of unfiltered restrictors.

In addition, the AD mandated embodiment of a further DAC SB, No 32-278 which modified the shimmy damper. SB 32-278 appears to address MLG torque link failures resulting from shimmy and no reference is made to the phenomenon of 'gear walking'. The AD required both modifications on the basis that they 'reduce the possibility of vibration of the main landing gear that can adversely affect its integrity'.

Following the accident to G-DEVR (on 11 September 1995), DAC issued Alert Service Bulletin (ASB) 32A286, which called for magnetic particle and fluorescent dye-penetrant crack-detection checks of the MLG cylinders on all MD-80 series aircraft. Only the 'critical' areas were required to be checked and the techniques involved removal of the paint and primer coats (but not the Cadmium plating) prior to accomplishment. Associated FAA Airworthiness Directive (AD) 95-22-06 was issued with an effective date of 8 November 1995, which made the requirements of the initial release of the ASB mandatory.

Aircraft which had never had brake line restrictors installed were required to be checked within 90 days of the effective date and thereafter at intervals not exceeding 1,200 landings, assuming no cracks were found. Subsequent fitment of the restrictors immediately after the inspection then obviated the requirement for further checks. Aircraft which already had restrictors fitted were also required to be subjected to a once-off inspection within 90 days. Any cracked cylinders were required to be removed prior to further flight and the FAA or the manufacturer notified. During discussion with BCA at the beginning of the EC-FXI investigation it was stated that no reports of cracks being discovered as a result of the AD had been received to that date (see paragraph 1.16.1).

AAIB Accident Report 1/97 contained the following Safety Recommendation:

> It is recommended that the FAA review AD 95-22-06 with a view to requiring repeat inspections of the Main Landing Gear, even after fitment of restrictors to braking systems, on landing gears which have been operated without them. (Safety Recommendation 97-2)

On 27 April 1997, whilst the FAA were considering the above Safety Recommendation, the accident in China occurred (paragraph 1.6.4.4) and

ASB 32-A286 was revised to re-introduce the Non-Destructive Examination (NDE) inspections at 1,200 landing intervals on cylinders that had been operated without restrictors. A new FAA AD, number 96-06-13 effective 22 April 1999, was issued to mandate the ASB. The inspections were to continue for a minimum of 4,800 landings (ie four inspections). Information from the FAA advised that the reasoning behind this change was that, if embryonic cracks existed due to gear walking, they could have been too small to detect initially when accomplishing the original 'once-off' inspection. The figure of 4,800 landings was felt to be sufficient to allow any cracks to grow to a detectable size and therefore any cylinders showing no crack indications after this period should be crack-free and no further inspections would be necessary.

1.6.4.6 Service and maintenance history of the failed cylinder

The failed MLG cylinder from EC-FXI was serial number CPT 1509. It was received by the operator on delivery of another new aircraft, registration EC-FZC. This aircraft did not have brake line restrictors fitted and, therefore, when ASB 32-A286 was issued, the cylinders fell within the original requirement to inspect them. The inspection was carried-out on 15 January 1996 at 10,310 Cycles Since New (CSN) with no crack indications.

Installation of restrictors on EC-FZC took place on 9 September 1996 at 11,434 cylinder CSN.

On 6 May 1998, both MLG's were removed from EC-FZC and sent for overhaul, during which the cylinders received the series of Non-Destructive Examination (NDE) bench inspections forming part of the overhaul schedule and the opportunity was taken to concurrently satisfy ASB 32-286, now at revision 2, and requiring four repeat inspections. The cylinders had accumulated 14,589 CSN.

Both MLG's were then fitted to EC-FXI (which had now also had restrictors fitted) on 15 July 1998. The third mandatory inspection took place on 14 January 1999 at 15,769 CSN, and a fourth at 16,901 CSN on 31 July 1999. None of these inspections generated any reports of confirmed or suspect cracks.

CPT 1509 failed with a total of 20,145 CSN. The complete technical records for both EC-FZC and EC-FXI were reviewed for any significant MLG-related events but, apart from a few hard landing and overweight landing checks (none of which required any further action), there were no reports of severe or unusual vibration events recorded.

It should also be noted that the Maintenance Schedule called for a visual check of the MLG generally for '*general condition, attachment, leakage, corrosion* *and visual damage*.' It is considered highly unlikely that such an inspection would detect a crack, even at its maximum size immediately prior to failure.

1.6.5 Automatic landing

The aircraft was certificated for automatic landings with flap 40°. When performing an Autoland, a speed of V_{REF} +5 kt (in this case 133 kt) was required to be set on the airspeed command bug for the final approach. The maximum permitted tailwind for both automatic and manual landings was 10 kt. Furthermore the Operations Manual stated that if the tailwind limit is exceeded during an Autoland, then the Autopilot must be disconnected by 50 feet Radio Height (RH). The company Operations Manual also contained the following operational limitation:

> *'During coupled approach the autopilot must be disconnected if LOC TRK and G/S TRK has not been annunciated before passing 700 ft AGL'*

1.7 Meteorological information

The synoptic situation at 1200 hrs on 10 May 2001 showed an area of high pressure north of Shetland feeding a light east-south-easterly flow over the Liverpool area.

The Terminal Area Forecast (TAF), issued at 0912 hrs on 10 May 2001, valid for period from 1000 to 1900 hrs, included the following information: Surface wind from 060° at 10 kt, visibility greater than 10 km, scattered cloud base 3,000 feet.

The Aerodrome Meteorological Report (METAR) at 1220 hrs recorded the surface wind as variable at 3 kt, visibility 10 km, few clouds at 4,000 feet, scattered cloud base 9,000 feet, temperature +20°C, dewpoint +13°C and QNH 1019 mb. The next observation at 1250 hrs, 18 minutes after the accident, recorded the surface wind as being from 100° at 14 kt.

The Liverpool ATIS, copied by the crew prior to the approach, was coded 'Uniform', recorded at 1203 hrs and gave: '*Runway 09, surface wind variable 2 kt, visibility 15 km, cloud few at 4,000 feet, temperature +18°C, dewpoint +13°C, QNH 1019, QFE 1017, runway damp, damp, damp*.'

1.8 Aids to navigation

Liverpool Airport is equipped for Localiser only approaches on Runway 09 and for Category II ILS Approaches on Runway 27. Special ATC procedures are required for Low Visibility Operations on Runway 27, but these were not in force at the time of the accident, because good weather conditions prevailed. The crew was advised that there was no ILS protection in place prior to the commencement of the approach.

1.9 Communications

Recordings of the communications between both Manchester Area Control Centre (ACC) and Liverpool ATC with the aircraft were available for the investigation.

1.10 Aerodrome information

Runway 09 was the runway in use at the time of the accident. The aircraft landed on Runway 27 after a pilot request. The runway surface was dry, albeit reported as ‘damp’. The Runway 27 Landing Distance Available is 2,286 metres, with a width of 46 metres. The aerodrome category for Rescue and Firefighting (RFF) was category 7, which was suitable for aircraft up to 49 metres in length and was appropriate for the landing of the MD-83.

1.11 Flight Recorders

The two tape based recorders fitted to the aircraft, a half-hour CVR and a 25 hour FDR, retained a record of the accident. The recordings terminated after the aircraft had come to rest and both engines had been shut down.

In compliance with the applicable section of Joint Aviation Requirements (JAR) – Operations (OPS) 1, crew speech, other than when transmitting using the radios was only recorded on the area microphone channel of the CVR. The low quality of the recording from this source was such that very little of the flight deck conversations were intelligible. Under current UK regulations, all UK registered aircraft fitted with a CVR are required to be fitted with a system whereby speech from the crew boom microphones is continuously recorded, regardless of whether the radio push-to-talk is depressed. The absence of information pertaining to the approach and landing briefings discussed by the crew of the accident aircraft has precluded a more detailed analysis of the events. This was further compounded by the reluctance of the flight crew to assist in the accident investigation process.

A Safety Recommendation is therefore made that the Joint Aviation Authorities amend the relevant sections of JAR-OPS 1 with a view to requiring that all aircraft fitted with a Cockpit Voice Recorder record, without interruption, the audio signals received from each boom and mask microphone in use. [Safety Recommendation 2003-44]

1.11.1 Previous landings

The FDR retained a record of the nineteen landings made by the aircraft prior to the accident landing. The data from each landing was inspected for anomalous behaviour. No evidence was found of an event that may have contributed to the failure of the landing gear.

1.11.2 FDAU and parameter faults

During the course of the investigation it was noted that the Flight Data Acquisition Unit (FDAU) had shown an intermittent fault on some parameters. This fault manifested itself once all the parameters from the entire 25 hour FDR recording had been analysed and consisted of a single ‘bit’ error in any one of the recorded parameters for a period of time. Neither the ‘bit’ in error, nor the sample of the parameter with which it was associated, appeared to be predictable but, once evident, the fault repeated itself every second for some minutes. Interspersed throughout the 25 hour recording this fault appeared on normal acceleration, pitch and roll attitude. Where the ‘bit’ in error was one of the most significant ‘bits’, the problem was readily evident. However, it was not possible to determine whether there were errors in parameters in the lower order, less significant ‘bits’.

The equipment was returned to the manufacturer together with a complete copy of the raw FDR data for assessment. The FDAU was subjected to the applicable acceptance test procedure but no anomalies were found.

1.12 Examination of the aircraft

1.12.1 On-site examination

The aircraft was examined in-situ on the night of the accident at Liverpool Airport. It had come to rest on the right side of the runway with the right MLG failed, but was parallel to the centreline with the right wing tip just on the grass. Major damage to the airframe mirrored that observed on G-DEVR (which suffered a left MLG failure), comprising direct damage to the inboard flap caused by the wheels and considerable abrasion of the remaining flap trailing edges and some slat leading edges due to runway contact. The mainwheels were protruding through the torn right inboard flap and it could be seen that the MLG cylinder had fractured in an almost identical location to that experienced on G-DEVR. The separated lower half of the cylinder, including the wheels, remained attached to the airframe only by the severely twisted sidestay. Unlike G-DEVR, the contortions of the latter had forced-open the MLG door and this was ground-away to approximately half its normal length.

Examination of the runway marks could not definitely establish the point of touchdown - the first evidence of contact being a narrow, light mark of paint and aluminium caused by the right MLG door edge, close to where the witnesses reported the touchdown. The pilot seemed to have been successful in preventing the wing from dropping until a very late stage since no additional marks were found until about 200 metres from where it came to rest. These marks comprised a broadening swathe of aluminium and paint, clearly caused by the flaps and slats. The total ground roll was estimated to be about 1,600 metres. There had been no release of fuel and no evidence of fire.

The right wing was raised using airbags, allowing closer inspection of the cylinder fracture face. As with G-DEVR, the vast majority of the face bore signs of fast, ductile rupture, with distinctive ‘chevron’ features pointing towards an origin at the front face of the cylinder (Appendix C). Here, a small fatigue crack could be discerned, again similar in location and dimensions to the one observed on G-DEVR

1.12.2 Metallurgical examination

The lower half of the fracture face was despatched for metallurgical examination in the United Kingdom under AAIB supervision. The upper half was despatched to BCA for independent examination. Both subsequent reports agreed on the presence of a fatigue crack measuring 1.0 mm deep and 3.2 mm wide at the cylinder surface in the area identified on-site. There were multiple initiation sites within this major crack and, additionally, smaller fatigue cracks were identified either side of the major crack over a chord length of about 40 mm.

One feature which was noted was the presence of a growth band (visible as a distinct ridge) across roughly half of the crack depth (Appendix D). Analysis of this area using Energy-Dispersive X-ray showed the presence of quantities of Cadmium in the inner boundary of this area which were not present outside it.

Microsections of the material revealed a similar surface finish to that observed on the cylinder from G-DEVR, with the same smearing of the shot-peened finish caused by grit-blasting resulting in microscopic fissures, some containing embedded particles of alumina grit (Appendix E). These fissures were a maximum of about 20 microns in depth. The Cadmium plating was present but it was clear that the original paint finish had been removed (for previous crack checking) and that the re-applied finish was flaking-off in places.

Measurement of residual compressive surface stress due to the shot-peening process was achieved using an X-ray diffraction technique. This concluded that a compressive stress of 700 MPa existed at the surface, with a total depth of compressive stress of some 200 microns. This indicated a satisfactory peening result. However, the sample area was some distance removed from the fracture, whilst a similar test close to the fracture suggested that no residual stress existed. It was concluded that this anomaly was probably due to the mechanics of the fracture itself, or in cutting the sample, or a combination of both, as it was unlikely that the peening process would have missed the critical area when it was successful in an adjacent region.

Hardness measurement of the cylinder material showed an average of 572 HV (Vickers), equating to a tensile strength of 1,930 MPa (280 ksi). This compares with a typical tensile strength of 2,050 MPa for 300M material. Aircraft Material Specification (AMS) 6419 specifies a minimum strength of 1,930 MPa. Thus the cylinder material appeared to be at the bottom of the strength range for this alloy, but not out of limits.

1.13 Medical and pathological information

There were no relevant medical factors.

1.14 Fire

There was no fire.

1.15 Survival aspects

The aircraft was configured with 170 passenger seats, but only had 45 passengers and 6 crew on board. The passengers were all seated in the forward and centre sections of the cabin. The forward exit doors were opened by the cabin crew. No attempt was made to use the aft emergency exit doors. One passenger, who was seated next to an overwing exit, opened it and evacuated by this means.

During the evacuation, some uncertainty arose between passengers and crew as to the best method of evacuating small children or infants down the escape slides. This caused a short delay to the egress of passengers. There was no guidance for how to manage this in the passenger safety briefing or safety cards.

There has been very little research carried out on best practice for evacuation of small children and infants down escape slides. A recent study completed in November 2001 on behalf of the United States Department of Transportation (DOT/FAA/AM-01/18) concluded that the most rapid evacuations were achieved when children between the ages of 2 and 24 months were held by an adult who then jumped onto the slide. Sitting down holding the child prior to starting down the slide was found to destabilise the adult's hold on the child and to delay the evacuation process.

1.16 Tests and research

1.16.1 Examination of other cracked cylinders

During discussions with the FAA and BCA in the early stages of the investigation, it was stated that, arising from the programme of inspections following the accident to G-DEVR, there had been no reports of cracks being discovered as a result of the mandatory inspections worldwide.

However, since the AD required airlines and maintenance organisations to report any findings from the 'on-wing' inspections, it was queried whether workshops might be discovering cracks during cylinder overhaul and, because there was no instruction to report such information, cylinders could be being scrapped without coming to the attention of BCA or the FAA. The answer to this query was again negative - apart from the maintenance organisation responsible for Spanair and EC-FXI. It transpired that their MLG overhaul workshop had rejected three cylinders for crack indications in the critical area during 1998/99, but the organisation's Engineering Department was not aware of this fact, nor were they aware that one of the three cylinders had been submitted to workshops for confirmation of an indication found during an on-wing AD inspection.

AAIB visited the maintenance organisation to examine these three cylinders. Also, the left MLG from EC-FXI, the cylinder of which had now been removed for strip inspection/salvage, was subjected to workshop NDE using both a powerful magnetic particle inspection (MPI) bench test rig and typical 'in-field' equipment used to satisfy the AD requirement. It became apparent that, for economic reasons, the organisation was performing more NDE inspections than required during the overhaul process to prevent unnecessary work being done to a cylinder which might later be found to have a crack. This involved NDE inspections, both with and without the Cadmium plate present. The left MLG cylinder from EC-FXI was thus inspected initially with the plating present but with the paint removed and no crack indications were found in the critical area. However, when the plating was removed, two small crack indications were discerned in the critical area at the front of the cylinder. This was so when using both the workshop and field equipment.

All four cylinders were despatched to BCA to confirm the crack indications. They initially repeated the inspections and, using MPI, all four cylinders showed crack indications, confirming the original findings. Other NDE method results (Fluorescent dye penetrant and Eddy-current) were more variable. It was then decided to section three of the cylinders, keeping one ‘in reserve’ for future reference, to examine the crack indications. The sections confirmed fatigue cracks in all cases.

1.16.2 Verification of stress levels during landing.

As part of the investigation into the accident to G-DEVR, the AAIB commissioned an independent analysis of the stress levels at the critical section of the cylinder, primarily to check that the component met the Federal Aviation Requirements (FAR), particularly for the braked-roll case. More detail on the findings of this report are contained in AAR 1/97. Since the failure on EC-FXI occurred at touch-down, before braking commenced, a further report was commissioned from the same organisation to examine the stress levels at touchdown, which are dominated by spin-up drag loads. To perform such an analysis simulating a ‘real’ landing would require considerable aerodynamic data with consequent complexity and margins of error. It was therefore decided to investigate the loads generated during a simulated ‘drop’ test, in which the mass of the aircraft falls under gravity from a pre-determined height and forward speed and is reacted by the landing gear. The loads generated could thus be compared with existing data from drop tests.

Quantification of these loads required detailed analysis of the FDR data and it emerged that, although the vertical accelerometer did not record any particularly remarkable values of vertical ‘g’ during touchdown, the descent velocity, at 3.2 metres per second, was somewhat beyond the limit of 10 feet per second (3.05 metres per second) as defined in FAR 25.473. However, the study concluded that the loads generated on touchdown were not sufficient to have failed the cylinder without the presence of a flaw of the size known to have existed in the accident component. Indeed the calculations re-confirmed the critical loading generated during the braked roll case implying that, had the cylinder not failed on this touchdown, it could have failed at the next application of heavy braking.

Apart from the limitations of the load calculations mentioned above, the analysis used simple elastic engineering bending theory and the effects of geometric and material non-linearity were not taken into account. It was noted that the cylinder design, in the critical area, only yielded a Reserve Factor of more than one if a Form Factor was applied. Reserve Factor is the ratio of the material ultimate tensile strength to the applied principal stress. The term Form Factor is used in a more detailed stress analysis that takes into account plastic yielding of the material and consequent non-linearity. This would be expected to improve the Reserve Factor. Because of the unknown effects of such parameters as Form Factor, the report recommended that a MLG ultimate load test should be performed to measure the actual loads that cause failure and hence physically measure the effect of these variables. This recommendation is reflected in Section 4.

1.16.3 Effects of surface treatment and finish on 300M material

AAR 1/97 contained the following recommendation:

> It is recommended that the FAA/CAA promote and co-ordinate an industry study into developing suitable surface treatment processes for highly loaded, high tensile steel components to achieve fatigue resistance and surface protection without the introduction of stress-raising features. (Safety Recommendation 97-1)

The reason for this recommendation was that the metallurgists working for the AAIB during the G-DEVR investigation felt that, based on the micro-sections of the surface, the grit-blasting operation performed prior to Cadmium plating was causing a high degree of smearing of the peened finish, leading to sharp-edged voids and even embedded alumina grit, which were potential initiation sites for fatigue. Indeed, in the opinion of the AAIB's metallurgists, it could be seen that embryonic fatigue cracks were growing from some of the deeper and sharper stress-raising voids.

In response to the recommendation, the CAA commissioned a paper entitled '*Effects of surface treatments on the fatigue life of an ultra high strength steel 300M used for landing gear components*' from the University of Birmingham. It was published as CAA Paper 2000/6 in March 2001. Rather than seeking to explore different ways of finishing high-strength steels, the study concentrated on the effects on fatigue life of shot-peened and grit-blasted surfaces using both literature searches and some short-term experimental testing.

Possibly due to a misunderstanding over the intention of the recommendation, the study spent some time in establishing that shot-peening has a beneficial effect on fatigue life. The G-DEVR report never intended to challenge this premise, but was concerned with the grit-blasting operation (apparently necessary prior to Cadmium plating), which was introducing stress-raising features into the surface. The study's findings were very similar to those presented by the MLG manufacturer to the AAIB during the G-DEVR investigation, inasmuch as it was concluded that surface roughness introduced by the grit-blasting process was acceptable because it occurred within the residual compressive stress layer induced by peening and may even enhance these stresses. Grit-blasting is necessary to prepare the surface for Cadmium plating and there is, as yet, no single direct substitute (for Cadmium) available.

The report did acknowledge that, where the residual compressive stress may be compromised by compressive plastic deformation during an overload condition (heavy landing or severe 'gear walking'), the increased surface roughness of a grit-blasted finish could reduce the fatigue life when compared to a peened finish. An interesting observation was made that, where the stresses applied to propagate fatigue are low, the crack initiation sites tended to be sub-surface at roughly the limit of the compressive layer. Where the stresses were high, the initiation sites were found to be at the surface and the study concludes that this could be due to relief of the compressive layer due to plastic deformation, ie the case mentioned above. BCA point-out, however, that strain gauge data extracted from deliberate 'gear walk' events (during tests in support of the G-DEVR investigation) did not record levels of compressive stress in the critical area sufficient to cause yielding of the material.

Unfortunately, the testing undertaken by the study did not include coupons prepared with a 'grit-blasted but not peened' finish. As a result, it was not possible to quantify the fatigue-life reduction likely to occur due to grit-blasting in the case where the shot-peening effect has been compromised by plastic deformation due to overload. It also has to be acknowledged that it would be very difficult to replicate the surface finish found on the cylinders without shot-peening, following which the residual stress would have to be removed without mechanically damaging the surface.

1.17 Organisational and management information

The company Operations Manual is produced to comply with the requirements of JAR-OPS 1. The manual contains Standard Operating Procedures (SOPs) for crews and also defines criteria for a stabilised approach. The following instruction is given:

> *'If the approach is not stabilised when passing 500 ft RH or if it becomes unstable in an instrument approach close to minima a go-around shall be made.'*

One of these stabilised approach criteria is as follows:

> *'Speed: Maximum deviations plus 20 kt and minus 5 kt from corrected final approach speed.'*

The usual company practice was for automatic landings to be conducted from the left hand seat although first officers were given the opportunity to practice them in the simulator.

In this case, the aircraft was at a speed of 176 kt at 500 feet RH (Radio Height), which was over 40 kt fast, but the crew continued to a landing.

1.18 Additional information

1.18.1 Sphere of operation of the aircraft.

The company operated in the European scheduled and inclusive tour market. Load factors were generally high and tankering fuel for commercial reasons was also common practice. Thus, a relatively high proportion of flights tended to involve operation of the aircraft at higher than ‘fleet average’ operating weights.

1.18.2 Post-accident inspection proposals

On 16 May 2001, following the accident to EC-FXI, the AAIB made the following Safety Recommendation:

Safety Recommendation 2001-54

> It is recommended that the Federal Aviation Authority and the Boeing Commercial Airplane Group urgently review the continued airworthinesss of the MD-83 MLG strut. In particular, the need for repeat inspection of the strut in the critical area be considered and the ability of the mandated NDE inspection to detect embryonic fatigue cracks in the material, given the small critical crack size, should be re-assessed. (Safety Recommendation 2001-54)

BCA issued, on 31 March 2003, a new ASB, No MD80-32A344, which re-introduces a repetitive inspection regime on MLG cylinders which have, at any time, been operated on aircraft not equipped with brake line restrictors. Compliance dates and repeat intervals are variable according to the number of cycles the cylinders have operated since fitment of the restictor. BCA advised that they expect the FAA to then issue an AD mandating compliance.

Amongst the changes in this latest ASB, it is noted that the new technique calls for the Cadmium plating to be removed prior to inspection and, assuming no cracks are found, to be reapplied afterwards.

2 Analysis

2.1 Flight crew operating technique

There was no evidence to suggest that the operating procedures were inadequate or that the way in which the flight crew operated the aircraft contributed to the accident.

The runway in use at the airport was Runway 09, in accordance with the actual and forecast surface wind conditions. The reason for the flight crew requesting an approach for Runway 27 for Autoland training purposes was not determined. It was not a training flight and there was no requirement for first officers to conduct Autolands during line flights.

The crew perceived the approach and landing to have been normal until a few seconds after touchdown. In fact, the surface wind exceeded the tailwind limitation for the aircraft, but this was not observed by the crew. There were indications however, prior to the surface wind information from ATC, that should have made it apparent to the crew that they were operating in tailwind conditions. The approach speed was fast and the aircraft could only maintain the glideslope with the thrust at idle power, which was not a normal final approach power setting. As a result, final flap configuration of the aircraft, and of the Autoland annunciation 'LOC TRK and G/S TRK' was delayed until 550 ft agl, which was below the Operations Manual stated requirement of 700 ft agl. The approach speed was over 40 kt in excess of the target speed of 133 kt at 500 feet RH and thereby did not meet the company stabilised approach criteria (a maximum of plus 20 kt). These factors should have acted as a trigger to the crew to disconnect the Autopilot and carry out a go-around.

Following the landing, upon recognition that there was a problem, the commander took over control of the aircraft. His inputs on the rudder and the brakes contributed to the aircraft maintaining its direction along the runway.

2.2 Human factors

Neither flight crew member could recall hearing any aural warnings or cautions during the latter part of the flight or after landing. The first audio warning was a single "LANDING GEAR" annunciation generated as a result of the speed and height of the aircraft. This caution may have been familiar to the crew from occasions on previous flights and thereby disregarded as insignificant.

The next aural input that might have triggered a response from the crew was that from ATC who passed a landing wind which was in excess of the landing tailwind limitation for the aircraft. This was probably not assimilated by the crew as there was no concern expressed by them on receipt of the information. The final audio warnings, which took place after the landing gear had collapsed, were continuous alternating "LANDING GEAR" and "AUTOPILOT". These appear to have been blocked out by the crew as they concentrated their efforts on controlling the aircraft and dealing with the unexpected emergency situation.

The lack of co-operation of the flight crew with the investigation could have been as a result of a lack of understanding of the purpose and progress of accident investigation. It is essential that witness evidence is obtained at an early stage to be of significant use because of the corruption of memory with the passage of time.

2.3 Aircraft evacuation

The evacuation in this case was carried out efficiently. However, the passenger load was very light and there was no fire.

The absence of any guidance as to the best way to manage the evacuation of infants and small children led to confusion and could have caused a delay to the evacuation. In this case it did not cause a significant delay, probably because the aircraft was less than one third full.

In view of the current lack of information available to crews and passengers regarding the evacuation of small children and infants it was felt that some guidance should be made available. At present the relevant research has produced results that could be used to provide some best practice information. This information could increase the confidence of passengers and crews in the process of evacuating small children from aircraft.

A Safety Recommendation is therefore made, that the CAA, JAA and the FAA should provide guidance as to the recommended best practice for the evacuation of infants and small children down escape slides with minimum delay. [Safety Recommendation 2003-48]

2.4 MLG cylinder failure

Although the touchdown was heavier than normal and, initially, on the right MLG only, the calculations suggested that it was not sufficiently severe to have failed the cylinder without the pre-existence of the fatigue crack. The same calculations also re-iterated the findings from the previous exercise conducted following the accident to G-DEVR, inasmuch as the highest bending loads at the critical section normally arise from heavy braking rather than touchdown. The two previous cases of failure occurred during braking.

It is unknown why the failure occurred at this stage of the landing, but in most other respects the accident to EC-FXI is almost identical to the other two, characterised by a major fatigue crack from multiple origins being present in the critical area at the front of the cylinder. The ultra-high tensile strength steel, 300M, used in manufacture of the cylinder, is known to be highly sensitive to defects such as fatigue cracks and so, whilst appearing to be small in relation to the material cross-section, the crack was sufficient to compromise the overall strength of the component under in-service loads which would otherwise not have led to failure.

The explanation offered in AAR 1/97 for the development of the crack was that a few cycles of severe loads (most probably 'gear walking') had propagated cracks through the residual compressive stress layer and that normal operational loads were then able to increase the size of the crack to a critical level. However, the University of Birmingham study suggested that these same overload conditions could cause local permanent relief of the compressive layer, in which case the surface roughness of the grit-blasted finish would serve as initiation sites and propagation could take place without the need to assume that a number of load reversals are required to propagate a crack through the compressive layer. As stated in AAR 1/97, the assertion that the effects of increased surface roughness due to grit-blasting were not significant, because they occur in the region of compressive stress implies that, far from being considered a 'bonus' to fatigue life, shot-peening is *essential* to protect against propagation of fatigue from these surface irregularities, if it is assumed that the component would still be Cadmium plated, even if it were not peened. The study did not, however, pronounce on how great the reduction, if any, in fatigue life might be for a specimen which was peened and grit-blasted but subsequently lost the beneficial effects of the peening. Further evidence that this could have been the mechanism by which the cracks propagated stemmed from two observations:

(a) The crack origins were at the material surface, pointing to high applied loads in a properly peened surface or the absence of compressive stresses with more moderate loads.

(b) No residual stresses were measured in the immediate vicinity of the crack (although this could have occurred during rupture).

During the G-DEVR investigation, some consideration was given to devices which claimed to be able to measure residual stress non-destructively (Barkhausen effect). Using such a device, which measures minute changes in the magnetic field surrounding stressed components, it would be theoretically possible to detect the presence, or absence, of residual peening stresses and hence a component which has been plastically deformed or improperly peened.

Although such consideration was admittedly minimal, it did not appear that any machines available at the time were suitable for accomplishing in-field checks of the area considered critical on the MD-80 series cylinders. The possibility that the residual compressive stresses induced by shot-peening could be lost under in-service conditions is not well understood or even proven, hence the AAIB make the following Safety Recommendation:

> The FAA and CAA should promote an industry study into the possibility that beneficial residual stress fields induced by shot-peening could be relaxed under in-service conditions. [Safety Recommendation 2003-45]

The mathematical studies commissioned by AAIB following both cylinder failure accidents which occurred in the UK, concluded that the strength of the component in the critical area was marginal, relying on allowances being made for such things as reduced braking co-efficient and Form Factor before an acceptable Reserve Factor could be demonstrated. The most direct way of eliminating many of these variables is to conduct an 'ultimate load test' to determine the strength of the cylinder. It could be argued that ultimate load tests supply information about static strength and not fatigue life but, when using a material which is well-known for its intolerance to defects, the two are not so easily divorced. The stress figures which were used to calculate the static strength were also used to calculate the fatigue life, in the absence of a full-scale fatigue test: any errors made about the stress levels experienced at the critical area would affect these calculations.

Therefore the following Safety Recommendation (2003-47) is made:

> Boeing Commercial Airplanes should conduct an ultimate load test on a suitable MD-80 series MLG cylinder to determine the strength of the component and to verify the figures used in both the original static strength and fatigue life calculations. (See Section 4.) [Safety Recommendation 2003-47]

2.5 Non-Destructive Examination

Conclusions concerning the events which initiated the fatigue crack were reached during the G-DEVR investigation. 'Gear walking' was considered the most likely abnormal event which could have generated the loads necessary to propagate the fatigue through the compressive layer, if it was assumed that the cylinder design actually resulted in routine operating stress levels consistent with those used to calculate the fatigue life (as was asserted by the manufacturer).

It was not considered that every aircraft in the worldwide fleet had been subjected to ‘gear walking’ and that a once-off NDE examination would identify and eliminate those that had been damaged by this mechanism.

Safety Recommendation 97-2, contained in AAR 97/1, reflected the AAIB’s concern that a once-off inspection might be unable to detect cracks which were too small but which might propagate to failure. Whilst this was being considered by the FAA, the second failure occurred in China and BCA and the FAA amended the ASB and raised a further AD respectively to require a total of four repetitive inspections of the area. It was considered that this would be sufficient to identify any cracked cylinders and that any which still appeared crack-free after this period would remain so, now that every aircraft was fitted with restrictors which were shown to suppress any tendency to ‘gear walk’.

It must be of concern that this repetitive regime of inspections failed to detect the crack which caused the failure on EC-FXI, which had completed the prescribed number of inspections and was therefore considered crack-free. The presence of Cadmium in the crack face could be interpreted as evidence that the crack, then (by implication) roughly two-thirds of its length at failure, was missed during the overhaul NDE, but BCA presented a mechanism by which surface Cadmium could migrate into the crack due to saline moisture action. Whichever interpretation is correct, it is probable that a crack of some size, at least, existed during the overhaul, which even the more efficient equipment and suitable working environment of a workshop failed to detect. Two further ‘on-wing’ inspections also failed to find indications of a crack.

Also of interest was the fact that the overhaul shop had found small cracks in two cylinders and confirmed an on-wing indication in another. These remain the only cracks that have been found by inspection and notified to the FAA and BCA prior to this accident. It would be hard to accept that, given the large number of MD-80 series aircraft produced and in-service, these are the only cracked cylinders which exist outside the three fractures. The failure to notify the manufacturer or the authorities of the three cracked cylinders was due to a simple lack of internal communication between workshops and the operator’s engineering department in this particular case. They should be commended for finding and removing the cylinders from service, but the question posed is whether other inspecting agencies have been missing crack indications.

What is certain, however, is that early detection of cracks before they reach critical dimensions is vital in preventing MD-80 series MLG failures. The proposed new procedure should assist this and the requirement for repetition of inspections, which does not assume that cylinders are crack-free after a few negative results, should increase the probability of detection. The same applies to the revised procedure to remove the Cadmium plate prior to inspection.

3 Conclusions

(a) Findings

1 The aircraft was properly maintained and was serviceable prior to the accident.

2 The aircraft was correctly loaded and its documentation was in order.

3 The flight crew were properly licensed, medically fit and adequately rested to conduct the flight.

4 There was no evidence to suggest that the company Standard Operating Procedures were inadequate, despite the indications that the final approach was not correctly stabilised, or that the way in which the flight crew actually operated the aircraft contributed to the accident.

5 The Standard Operating Procedures criteria laid down in the Operations Manual for an Autoland and a stabilised approach were not achieved during the approach.

6 The first touchdown occurred on the right MLG with an aircraft roll attitude of 2.6° right wing down. The landing, whilst described as 'severe', should not have resulted in failure of the main landing gear under normal circumstances.

7 The right main landing gear oleo cylinder failed immediately upon touchdown due to the presence of a 3.2 mm long by 1.0 mm deep fatigue crack in a critical area at the front of the leg, just below the attachment trunnions.

8 The material from which the cylinder was forged, whilst possessing very high tensile strength, is sensitive to relatively small defects such as fatigue cracks.

9 The crack had not been detected either by four mandatory NDE inspections, or by routine visual examination. It is also possible that the crack was missed during a workshop overhaul some 5,556 landings prior to this failure.

10 This was the third case of an MD-80 series main landing gear failure due to fatigue cracking in the subject area.

11 After the accident, the left main landing gear cylinder from EC-FXI was found to have two small cracks in the critical area, but these were discovered only after removal of the Cadmium plating.

12 One overhaul agency had found three confirmed cases of cracking of main landing gear cylinders in the critical area but, due to an oversight, they had not been reported to the aircraft manufacturer, the national airworthiness authority nor the FAA. No other operators or overhaul agencies reported finding crack indications when specifically questioned after the accident to EC-FXI.

13 The fracture bore many similarities to those of another cylinder failure which occurred in April 1995 and which was the subject of an AAIB investigation. A further failure which occurred in China in 1997 also bore many common features.

14 Measures undertaken by the aircraft manufacturer and the FAA following the above two accidents did not prevent this third failure. Assumptions that cylinders would be crack-free following four negative NDE inspections, and after installation of brake hydraulic line restrictors, appear to have been erroneous.

15 The small critical crack size, coupled with an unknown growth rate, made detection of cracking by NDE, before complete failure, extremely difficult using the then-specified procedure.

16 The proposed revised inspection procedure and periodicity, should enhance the probability of detecting a crack prior to failure of the cylinder.

17 The absence of residual shot-peening compressive stress adjacent to the fracture may have been the result of the material rupture. However, it might also have dissipated in-service, due to abnormal loading or some other combination of factors which are not currently understood

18 The source of such abnormally high loads was probably the previous occurrence(s) of ‘gear walking’. However, until the precise strength and

fatigue characteristics of the cylinder are measured by destructive ultimate load tests, the possibility cannot be ruled-out that the critical area of the cylinder is subjected to higher stresses under normal loading than was predicted in the original fatigue life calculations.

19 Even though a successful passenger evacuation was carried out in this case, a difficulty arose with the evacuation of infants which could have led to an unacceptable delay on an aircraft which had a full complement of passengers.

(b) Causal Factors

The following causal factors were identified:

1 The right main landing gear cylinder failed immediately upon touchdown due to the application of spin-up drag loads on a section of the cylinder containing a major fatigue crack 3.2 mm long and 1.0 mm deep and several other smaller cracks associated with it.

2 The origins of these fatigue cracks could not be identified but other embryonic cracks were found which were associated with surface irregularities arising from a grit-blasting process during manufacture. Abnormal loading, possibly due to an occurrence of a mode of fore-and-aft vibration known as ‘gear walking’ is thought to have been responsible, at some time in the aircraft’s history, for propagating the cracks to a depth at which continued growth was possible under normal loading. Alternatively, some abnormal loading may have relaxed the beneficial compressive surface stresses induced by shot-peening at the critical section and allowed propagation from the same surface defects.

3 Inspection and other mandatory preventive measures taken following two similar accidents did not prevent the occurrence of this third accident. This was probably due to the small size of cracks which are required to be detected before reaching a critical dimension.

4 Safety Recommendations

The following safety recommendations have been made:

4.1 **Safety Recommendation 2001-54** (made on 16 May 2001): It is recommended that the Federal Aviation Administration and the Boeing Commercial Airplane Group urgently review the continued airworthiness of the MD-83 main landing gear strut. In particular, the need for repeat inspection of the strut in the critical area be considered and the ability of the mandated Non-Destructive Test inspection to detect embryonic fatigue cracks in the material, given the small critical crack size, should be re-assessed.

4.2 **Safety Recommendation 2003-44**: It is recommended that the Joint Aviation Authorities amend the relevant sections of JAR-OPS 1 with a view to requiring that all aircraft fitted with a Cockpit Voice Recorder record, without interruption, the audio signals received from each boom and mask microphone in use.

4.3 **Safety Recommendation 2003-45**: It is recommended that the FAA and the CAA should promote an industry study into the possibility that beneficial residual stress fields induced by shot-peening could be relaxed under in-service conditions.

4.4 **Safety Recommendation 2003-47**: It is recommended that the Boeing Commercial Airplane Group should conduct an ultimate load test on a suitable MD-80 series main landing gear cylinder in order to determine the strength of the component and to verify the figures used in both the original static strength and in the fatigue life calculations.

4.5 **Safety Recommendation 2003-48**: It is recommended that the CAA, JAA and the FAA should provide guidance as to the recommended best practice for the evacuation of infants and small children down escape slides with minimum delay.

P D Gilmartin
Inspector of Air Accidents
Air Accidents Investigation Branch
Department for Transport
October 2003

Unless otherwise indicated, recommendations in this report are addressed to the regulatory authorities of the State having responsibility for the matters with which the recommendation is concerned. It is for those authorities to decide what action is taken. In the United Kingdom the responsible authority is the Civil Aviation Authority, CAA House, 45-49 Kingsway, London WC2B 6TE