ACCIDENT

Aircraft Type and Registration:	Bombardier BD700 Global Express, VP-CRC
No & Type of Engines:	2 Rolls Royce BR 710 series turbofans
Year of Manufacture:	2007
Date & Time (UTC):	29 January 2008 at 0808 hrs
Location:	London Luton Airport
Type of Flight:	Private
Persons on Board:	Crew - 3 Passengers - 1
Injuries:	Crew - None Passengers - None
Nature of Damage:	Left inboard main landing gear tyre burst, flap drive shaft and two hydraulic pipes fractured, wiring loom damaged and localised wing structural damage
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	36 years
Commander's Flying Experience:	3,759 hours (of which 92 hrs were on type) Last 90 days - 78 hours Last 28 days - 38 hours
Information Source:	AAIB Field Investigation

Synopsis

Following an extended period of heavy rain, VP-CRC took off from a dry runway for a long-range flight to London Luton Airport. During the subsequent landing roll, the left inboard main landing gear tyre suffered a slide-through failure resulting from an initially locked wheel. This tyre failure caused extensive damage to the flight control system. Although the aircraft landed safely, the investigation revealed a significant flight safety risk and four Safety Recommendations are made.

History of the flight

VP-CRC departed Van Nuys, California at 2240 hrs and arrived at London Luton at 0808 hrs on the following day. The flight had been without incident. Shortly after a normal touchdown on Runway 26, the crew became aware of a rumbling noise which they identified as a burst tyre. Simultaneously an aircraft at the holding point reported by radio that VP-CRC had suffered a tyre burst. The commander applied normal braking and 15 seconds after touchdown, the Nos 2 and 3 hydraulic system low pressure Engine Indication and Crew Alerting System (EICAS) messages displayed. The commander brought the aircraft to a stop on the runway using normal brakes and, as fire vehicles approached, shut down both engines.

Tyre failure and associated damage

The AAIB investigation revealed that an inboard main-wheel tyre suffered a slide-through type failure resulting from a locked wheel. This developed into a larger disruption of the tyre carcass which in turn resulted in flailing of a substantial section of both tread and carcass when the wheel then began to rotate. The flailing material struck the spray guard at the rear of the auxiliary spar below the inboard ground spoiler a number of times. This destroyed the guard, inflicted significant damage to the wing local auxiliary spar structure and fractured hydraulic pipes resulting in Nos 2 and 3 hydraulic systems becoming inoperable. It also fractured the flap drive torque tube, damaged a major wiring loom and caused metallic debris to be forced between and into contact with the two cables driving the left aileron.

The tyre in question was of the cross-ply type, sometimes known as a Bias ply type.

The landing took place on a dry runway of generous length for the aircraft type. Examination of the relevant components and the flight data recorder (FDR) led to the conclusion that the aircraft touched down with the left inboard wheel locked and that it became free to rotate shortly after the tyre ruptured. The locked condition of the wheel does not appear to have been the result of high hydraulic pressure being supplied to the associated brake. Between the touchdown and the tyre failure, the recorded brake pressure supplied to this unit remained low and almost identical to that supplied to the brake on the neighbouring wheel, the tyre of which was undamaged. Detailed examination and functioning of the brake unit from the wheel on which the ruptured tyre was mounted revealed no evidence of damage or malfunction. In particular the brake pistons released fully and correctly as hydraulic pressure was released, following every one of a series of simulated brake applications carried out on a test rig.

The AAIB is concerned that a similar failure sequence occurring during a 'touch-and-go' landing, or a comparable extent of tyre failure occurring, for different reasons, at a late stage during a takeoff run, could inflict damage to flying controls, hydraulic services and electrical conductors, sufficient to cause reduction or total loss of control either before or after takeoff.

The manufacturer's analysis of a similar failure is that the aircraft would remain controllable. They state that:

> *'a loss of control command to the spoiler control PCU's will cause the PCU's to default to safe mode (retracted) and redundant monitoring channels of the spoiler control system will prevent spoiler runaway. A loss of hydraulics would result in a slow and graduate drift of spoiler surfaces to aerodynamic neutral over time due to internal leakage.'*

The AAIB's rationale for their concern is described more fully later in this bulletin in the section titled 'Effect of damage on controllability'. The section 'Additional matters arising' is also relevant.

Slide-through tyre failures

A slide-through failure occurs in a tyre following an extended period of ground motion with a locked wheel. This results in concentrated local wear of the tread, creating an elliptical 'flat spot'. If the wear is sufficient for the centre of the elliptical area to penetrate into the carcass, the thickness of the latter will reduce locally, causing the stresses created by the inflation pressure to increase. With sufficient wear, these stresses will exceed the tensile strength of the remaining material in the region of the centre of the ellipse. Bursting failure thus occurs, with tearing of the carcass emanating from the centre of this wear pattern, generally radiating in four directions, each following the diagonal orientation of the tyre reinforcing plies.

In certain cases these diagonal tears extend through the tyre shoulder area, into and through the sidewall. On reaching the reinforcing beads at the junction of the sidewall and the wheel, the tear may change direction, again following the orientation of plies, propagating back towards the tread. Regions of sidewall, approximately V shaped, will remain attached to the separated section at the shoulder of the tread. The tread generally provides sufficient reinforcement to arrest the tear as it re-crosses the shoulder, leaving the separated section of tread and carcass securely attached, via the region of carcass below the tread, to the remainder of the tyre. Should the wheel become unlocked, rotational flailing of this attached section of tread and carcass inflicts damage on anything it strikes. The magnitude of the damage is dependant on the mass of the flailing material, local strength of the tyre chords and the wheel speed. Tyre strike angle influences the damage to a more limited extent and is affected by aircraft weight and speed at the time of failure.

Departure weather

The aircraft had been parked in the open at Van Nuys Airport, California for four days before its departure for Luton on the accident flight. During this period the wheels were chocked with the brakes off and approximately 118 mm of rain fell, 15.7 mm falling during the twenty-four hours prior to departure. Significant rain ceased eleven hours before takeoff and no rain fell during the last eight hours before departure. During the final eight hour period the surface wind averaged 10 kt, the temperature was +12° C and the dew point +3° C. It is therefore clear that although extensive heavy rainfall occurred during the stay at Van Nuys, the surface conditions were dry by the time the occupants boarded the aircraft. The FDR data shows that after engine start, the aircraft taxied with minimal brake application. After takeoff it climbed rapidly to FL 410 for the 9.5 hour cruise to the UK.

Taxi technique

It is common practice, in business jet operations, to avoid using brakes wherever possible. The manufacturer's Operations Reference Manual (ORM) for the BD700 includes a section titled 'adverse weather' which advises use of the brakes during the taxi to warm the wheels in order to avoid 'frozen brakes.' This advice states 'monitor BTMS (Brake Temperature Monitoring System) during taxi' but there is no information detailing to how high a figure the brake temperature should be raised. Situations where the aircraft is parked only a short taxi distance from the holding point are not considered and the manual advises a 10 kt taxi speed which would provide little kinetic heating of the brakes. This information only applies on surfaces 'contaminated or covered with water'. At the time of departure the weather conditions were not adverse and the runway was not contaminated or covered in water. It should be noted that the ORM is produced for training purposes only; the Airplane Flight Manual and the Flight Crew Operating Manual are the documents intended for use by the flight crew in normal operations.

Previous events

It is understood that a similar aircraft type suffered a tyre rupture on arrival in Switzerland from Saudi Arabia, having departed shortly after it was washed. No fault was found in the brake system and it was concluded that the tyre failure resulted from freezing of water in the brake area during the flight, leading to locking of a brake unit.

The manufacturer reported that the crew completing the washing was unsupervised and did not protect the brake assemblies as required in the recommended cleaning procedures. However, this event illustrates the effect a high level transit can have on initially wet carbon-carbon brakes.

A landing accident occurred in Taiwan to a similar aircraft when it is understood that a defect in a brake control valve led to locking of a wheel which produced a slide-through tyre failure followed by flailing damage. This resulted in fracture of lines serving two hydraulic systems together with destruction of the wiring looms supplying signals to the spoilers on the left wing. Loss of steering and brake supply pressure led to depletion of brake accumulator pressure during the landing roll, resulting in the aircraft leaving the paved surface at a low speed.

Water flow analysis

It has been determined that when stationary, water on the wing upper surface flows inboard and aft until it reaches the hinge line of the spoilers. It then descends between the fixed structure and the spoilers and onto an aft projection of the bottom wing skin. This has a cusped rear edge, creating a gutter. The water then flows inboard along the gutter as a result of the wing dihedral.

Close to the wing root, the water encounters a number of projections which dam the flow. This has previously resulted in puddling, leading to extensive local corrosion. In 2004 a modification was introduced on production aircraft and made available retrospectively. This involved drilling a drain hole to allow the puddled water to escape. It has been found in practice, however, that after passing through the drain hole, much of the water flows inboard along the lower skin of the wing. Only when it encounters a flush skin joint which creates a small gap in the surface, does some or all of the water fall from the wing surface. This point is above the main landing gear and the water tends to fall onto the outboard wall of the inner tyre. This mechanism is believed to have resulted in water migrating onto the face of the exposed stator and entering the cavity in the wheel within which the brake stators and rotors are housed.

Water absorption by carbon brakes

The brake manufacturers have confirmed that the materials of the rotors and stators, both being carbon type structures, are porous and slightly absorbent. After extensive water soaking they require a prolonged period of exposure to dry warm conditions to ensure that full drying takes place. Alternatively, significant braking action must be deliberately applied during taxiing before departure to ensure brake drying. It is important to be aware that, on this type, rainfall can cause wetting of the brakes even in light wind conditions when the brakes would normally be assumed to be sheltered by the wing structure. It is also important to be aware that the brakes remain saturated with water for a lengthy dry period after rainfall ceases and runways and taxiways become dry.

The FDR shows that only a brief and light application of the relevant brake took place during taxiing (at a speed of approximately 3 kt). Automatic brake application on the type then occurs for four seconds during retraction. It is concluded that the contact faces of the brake stators and rotors of the brake unit in question remained both wet and in close proximity as the aircraft climbed and the temperature in the wheel bay cooled to a sub zero level. The cruise took place at ambient temperatures below -25° C, which is presumed to have caused stationary and moving components to become firmly frozen together, leading to wheel locking and tyre slide-through on landing. Application of sustained torque to the locked wheel, or some effect of the tyre rupture process, presumably caused failure of the ice bond, allowing the wheel to rotate and the damaged tyre section to flail and destroy areas of structure and critical aircraft systems.

Additional matters arising

The AAIB was involved in the investigation of a catastrophic failure in a cross-ply tyre, leading to a fatal take off accident to a Concorde aircraft on 25 July 2000. This has drawn attention to considerable differences between possible tyre failure modes in practice and those assumed for certification purposes. The accident to VP-CRC has demonstrated the vulnerability of flight critical systems on the BD 700 to impact damage from flailing sections of tyre when failure of the carcass occurs. Such flailing can, in addition to the wheel locking cause described above, result from lateral cutting of tread and carcass following contact with debris. The kinetic energy imparted by flailing tyre carcass sections, to any aircraft components within the radius of flail, is a function of speed. Should such tyre damage occur at the higher runway speeds associated with takeoff, the resulting airframe and control system damage could be very much greater than that experienced by VP-CRC. Although the leading edge of the flap provides more shielding and protection to the auxiliary spar area when takeoff flap is selected than it does with landing flap (as in the case of the Luton event), it is not clear that the flap structure has sufficient strength to deflect a flailing portion of tyre and prevent systems damage.

The EASA certification rules dealing with consequences of tyre failure apply to a small section of the thin, relatively low strength tread material dis-bonding from an otherwise intact carcass. Failures arising from slide-through tyre ruptures and from lateral cutting inflicted by debris can involve partial or complete separation of large sections of total carcass thickness, incorporating substantial portions of sidewall. The flailing section therefore has considerable mass and is reinforced by the chords of the tyre carcass. It will thus inflict greater damage at a given speed than that considered in the certification assumptions. The failure on VP-CRC also demonstrates the greater vertical distance into the wing structure to which damage can be inflicted in practice, compared with the situation assumed by the certification rules.

During crew conversion training, the aircraft is likely to conduct a series of touch-and-go landings. A tyre failure occurring during such a landing for either of the above causes also presents the possibility of the aircraft becoming airborne with the damaged systems described above.

Effect of damage on controllability

Loss of Nos 2 and 3 hydraulic systems results in failure of half the spoilers associated with roll control, together with loss of one of the two ailerons and one of the two elevators. In addition the operating control surfaces retain only a single control actuator rather than the two or three units normally in use. The manufacturer commented that:

> *'Simulated double hydraulic failure flight testing has shown that adequate controllability exists for continued safe flight and landing.'*

The damaged wiring loom on VP-CRC contained conductors supplying signals to the multi-function spoilers on the left wing. If such control signals are lost in addition to the hydraulic system damage experienced on this occasion, the degree of reduction of roll control capability to the left is almost total; that to the right is significantly reduced and control authority in pitch is also greatly reduced. Obstruction of aileron cables is presumed to cause some degree of movement restriction or change of roll control force, adding to control difficulties. Fracture of the flap drive results in loss of available flap movement. In addition to the above, a substantial proportion of other hydraulic services are inoperable when Nos 2 and 3 systems lose pressure.

Although it may be argued that, in ideal circumstances, the aircraft remains controllable even with a substantial proportion of the total flight control system inoperative, such a multiple failure event occurring at a time of high crew work-load will not necessarily have a benign outcome. Such a combination of failures and consequent control difficulty, together with changed aircraft response characteristics, occurring just prior to rotation speed, would be particularly demanding. The large number of warnings and alerts being displayed on the flight deck would also add to the complications faced by the flight crew, particularly on a departure in IMC.

The nature of the tyre failures discussed above apply to the cross-ply type of tyre construction. Tests have shown that the radial ply type of tyre does not possess this failure mode and that detached or flailing debris is likely to be significantly smaller and lighter.

Actions by the manufacturer

Following the accident, the manufacturer issued an Advisory Wire AW700-32-0244 on 19 March 2008, containing operational and maintenance information to counter the problem of freezing of wet carbon brakes. The Advisory Wire includes the following information:

'Description

Flight crews and maintenance personnel are reminded that carbon brakes can absorb or retain moisture. If a wet brake is not heated sufficiently to evaporate moisture from the disk surfaces, there is a possibility after in-flight cold soak or parking in known freezing conditions that the brake disk surfaces may freeze together. Should this occur, a subsequent taxi might produce a flat spot on the tyre or the subsequent landing may result in a tyre burst.

Action

Maintenance personnel are reminded to protect aircraft wheels and brakes from direct washing spray and inform the flight crew if the aircraft or landing gear has been washed recently.'

In accordance with the relevant Flight Crew Operating Manual, if the brakes have been exposed to moisture, flight crews are reminded to:

'During taxi, use light brake applications to warm the brakes before takeoff. Monitor BTMS during taxi.

When landing, carry out a positive landing to ensure initial wheel spin up and breakout of frozen brakes if icing has occurred.

During the landing roll and subsequent taxi, use brakes to prevent progressive build up of ice on the wheels and brakes. Monitor BTMS during taxi.

Following takeoff or landing on wet, snow or slush covered runways and taxiways: tyres should be inspected for flat spots prior to the next flight.'

Follow-up action

Following this accident, the manufacturer has published Advisory Wire AW700-32-0244 Revision 1. This includes the following additional information to the original advisory wire:

'Description:

Rainfall can cause wetting of the brakes, even in light wind conditions when the brakes would normally be assumed to be sheltered by the wing structure. After exposure to moisture, a prolonged period of dry warm conditions is required to ensure full drying takes place. Alternatively, brake applications must be deliberately applied during taxi, before departure, to ensure the moisture is evaporated away.

It is important to be aware that the brakes may remain saturated with water for a lengthy dry period after the rainfall ceases and the runways and taxiways have dried.

Action:

During taxi, use firm brake applications to warm the brakes before take off.

Bombardier will be revising the Global Express and Global Express XRS Flight Crew Operating Manual (FCOM) Vol 1. to introduce brake warming guidelines by revision 58, while the Global 5000 FCOM will be revised by revision 19. These revisions are scheduled for release September 15, 2008.'

These revisions have subsequently been released.

The following Safety Recommendations are made:

Safety Recommendation 2008-071

It is recommended that Bombardier introduce modifications to the BD700 to reduce the extent of concentrations of water pouring onto the outboard faces of the inboard main-wheel tyres and then onto the brakes when the aircraft is parked in rain.

Safety Recommendation 2008-072

It is recommended that Bombardier either

(a) Develop and implement modifications to the BD700 to effectively shield vulnerable flight critical hydraulic, electrical and mechanical systems in the vicinity of the main-wheel tyres against damage inflicted by items of large, full thickness, high velocity flailing tyre material and / or re-route some systems to minimise vulnerability to such events.

Or alternatively,

(b) Develop and require fitment to the BD700 and other Bombardier aircraft with similar features, a type of tyre that does not have such a flailing failure mode.

Safety Recommendation 2008-073

It is recommended that the Federal Aviation Administration, the European Aviation Safety Agency and Transport Canada raise awareness of the vulnerability of carbon brakes to freezing in flight following exposure to moisture on the ground, emphasising the significance of the slow drying rate of saturated brakes even in warm, low humidity conditions.

Cockpit Voice Recorder

The CVR was a solid state, 2-hour recorder which captured the last two hours of flight into Luton. The CVR system was powered by the aircraft DC essential power supply. The system included an 'impact' or 'g' switch interlock, designed to cut the power to the CVR in the event of a significant crash impact. The switch operates by sensing acceleration and removing the power supply to the CVR in the event of the acceleration exceeding 3g. The switch was mounted in the rear section of the aircraft, at a 45 degree incline to the longitudinal axis. The 3g threshold was therefore a combination of the aircraft's normal and longitudinal accelerations.

Upon arrival in Luton, the CVR recording ceased just after the nose landing gear touched down. The FDR recording showed a peak normal acceleration at touchdown of 1.2g and longitudinal acceleration peak, just prior to the loss of CVR, of -0.22g. When downloaded, the CVR operated normally and no cut in the aircraft DC essential power supply was reported. Maintenance records did not confirm the operation of the 'g' switch but system troubleshooting suggested that it was the most likely cause of the CVR stopping. The switch was subsequently removed from the aircraft and tested by the component manufacturer. Results confirmed that the switch operated successfully only when exposed accelerations in excess of 3g.

If the 'g' switch had operated, the FDR recorded accelerations did not show any evidence to support this. Equally, flight crew reports did not suggest a heavy landing and damage sustained by the aircraft was not consistent with a heavy impact. One explanation was that the accelerations recorded by the FDR 3-axis accelerometer may not correlate directly to those experienced at the 'g' switch. The FDR accelerometer was mounted in the landing gear bay, closer to the aircraft centre of gravity and accelerations were only recorded eight times a second. In the event of a high acceleration spike at some point during the landing roll, the FDR may not have recorded it.

According to the manufacturer, the 'g' switch was included to satisfy a certification requirement to stop the CVR automatically within 10 minutes of a crash impact. In the event of the 'g' switch operating, a red light illuminates on the switch and it then has to be manually reset by the ground crew.

While continued CVR recording would not have contributed significantly to this investigation, AAIB experience in the use of 'g' switches in CVR systems suggests they are not a reliable means of stopping the CVR.

The CVR system on VP-CRC was certified taking into account EUROCAE document ED56A (Minimum Operational Performance Specification (MOPS) for Cockpit Voice Recorder Systems). Section 6.2.11 of ED56A details 'Recorder Operation' and suggests that reliable means should be available for starting and stopping the CVR. To stop the CVR, ED56A includes a number of suggestions:

> *'a detection of loss of oil pressure on all engines together with loss of airspeed,*
>
> *b airframe crash sensors*
>
> *c water immersion sensors e.g. to detect ditching of the helicopter.'*

Specifically mentioned in ED56A is:

> *'The use of negative acceleration sensors ('g' switches) is not considered to be a reliable practice.'*

Although ED56A states that the use of 'g' switches is not 'reliable practice', it does not prohibit their use. The AAIB has encountered a number of instances in previous investigations[1], where 'g' switches have resulted in the loss of essential recorded information. Also, some foreign investigation authorities have encountered cases where flight recorders have stopped after the initial part

Footnote

[1] G-TIGK- AAIB Formal Report 2/97, G-BWZX - AAIB Bulletin November 1999, G-BMAL - AAIB Bulletin October 2001.

of a hard / crash landing so the remainder of the landing and /or passenger evacuation was not recorded.

As a result of the investigation and report into the accident to a Super Puma (G-TIGK) on 19 January 1995, the AAIB recommended to the CAA that the Combined Voice and Flight Data Recorder (CVFDR) 'g' switch was rendered inoperative (Safety Recommendation 97-32). The CAA did not accept this recommendation on the grounds that some recorders may continue running after an accident resulting in a crash impact, thus overwriting the recorded data.

As stated in the G-TIGK report, the AAIB was, and continues to be, unaware of any accidents where recorders would have continued to run after the crash impact had no 'g' switch been fitted. However, several accidents were encountered where premature operation of the 'g' switch had impeded the accident investigation. As a consequence, a further recommendation (Safety Recommendation 99-24) was made to the CAA requesting a reassessment of their initial response to Safety Recommendation 97-32.

The CAA response was to await the outcome of EUROCAE Working Group 50 (WG50) whose task was to issue the MOPS to supersede ED56A. The outcome of WG50 was to issue ED112, a MOPS for *'crash protected airborne recorder systems'*. WG50 was made up of international representatives from accident investigation authorities, airframe manufacturers, component manufacturers and aviation authorities. ED112 was issued in March 2003 and specifically references 'g' switches but more definitively recommends against their use:

> *'Negative acceleration sensors ('g' switches)* ***shall not be used*** *because their response is not considered to be reliable.'*

As a result, the following Safety Recommendation is made:

Safety Recommendation 2008-074

It is recommended that the Federal Aviation Administration and the European Aviation Safety Agency review the certification requirements for automatically stopping flight recorders within 10 minutes after a crash impact, with a view to including a specific reference prohibiting the use of 'g' switches as a means of compliance as recommended in ED112 issued by EUROCAE Working Group 50.