

AIRCRAFT ACCIDENT REPORT AND EXECUTIVE SUMMARY

				Reference:	CA18/2/3/9494	
Aircraft Registration	ZS-OAA	Date of Accident	26 October 2015		Time of Accident	9:54Z
Type of Aircraft	Boeing 737-400		Type of Operation		Commercial Part 121	
Pilot-in-command Licence Type	ATPL	Age	49	Licence Valid	Yes	
First Officer Licence Type	ATPL	Age	40	License Valid	Yes	
Pilot-in-command Flying Experience	Total Flying Hours	9186.1		Hours on Type	2899	
First Officer Flying Experience	Total Flying Hours	5817.1		Hours on Type	480.5	
Last point of departure	Port Elizabeth International Airport (FAPE)					
Next point of intended landing	O.R. Tambo International Airport (FAOR)					
Location of the accident site with reference to easily defined geographical points (GPS readings if possible)						
On runway 03R during landing at O.R. Tambo International Aerodrome						
Meteorological Information	Wind direction: 034°, Wind speed: 10kt; Wind Temp: 26°C; Visibility: 9999; Cloud cover: Few; Cloud base: 4500ft; Dew Point: 04°C					
Number of people on board	2+4+94+2	No. of people injured	0	No. of people killed	0	
Synopsis	<p>The Boeing 737-400, operated by Comair, flight number BA6234, was on a scheduled domestic flight operated under the provisions of Part 121 of the Civil Aviation Regulations (CARs). The departure from FAPE was uneventful, whereby the first officer (FO) was the flying pilot (FP) for this leg. During the approach to FAOR the aircraft was cleared for landing on runway 03R. The accident occurred at approximately 1 km past the threshold. The crew stated that a few seconds after a successful touchdown, they felt the aircraft vibrating, during which they applied brakes and deployed the reverse thrust. The vibration was followed by the aircraft rolling slightly low to the left. It later came to a full stop slightly left of the runway centre line, resting on its right main landing gear and the number one engine, with the nose landing gear in the air. The aircraft sustained substantial damage due to the separation of the left main gear resulting on the aircraft skidding on the left engine cowlings. No injuries were sustained by any of the occupants during the accident sequence.</p> <p>The investigation revealed that the accident was caused by excessive shimmy oscillations on the left landing gear, which caused it to fail.</p>					
Probable Cause						
Unstable approach whereby the aircraft was flared too high with high forward speed resulting with a low sink rate in which during touch down the left landing gear experienced excessive vibration and failed due to shimmy events.						
SRP Date	21 February 2017		Release Date			



AIRCRAFT ACCIDENT REPORT

Name of Owner : Comair Limited
Name of Operator : Comair Limited
Manufacturer : Boeing Aircraft Company
Model : 737-400
Nationality : South African
Registration Marks : ZS-OAA
Place : O.R. Tambo International Aerodrome
Date : 26 October 2015
Time : 0954Z

All times given in this report are Co-ordinated Universal Time (UTC) and will be denoted by (Z). South African Standard Time is UTC plus 2 hours.

Purpose of the Investigation:

In terms of Regulation 12.03.1 of the Civil Aviation Regulations (1997) this report was compiled in the interest of the promotion of aviation safety and the reduction of the risk of aviation accidents or incidents and not to establish legal liability.

Disclaimer:

This report was produced without prejudice to the rights of the CAA, which are reserved.

1. FACTUAL INFORMATION

1.1 History of flight

1.1.1 The aircraft Boeing 737-400, operated by Comair, flight number BA6234, was on a scheduled domestic flight operated under the provisions of Part 121 of the Civil Aviation Regulations (CARs). The aircraft was on the third leg for the day, after it had performed two uneventful legs. According to their recorded flight plan, the first leg departed from King Shaka International Airport (FALE) to O.R. Tambo International Airport (FAOR), the second leg was from FAOR to Port Elizabeth International Airport (FAPE) on the same day, during which the Captain was flying. During this third leg, the aircraft departed from FAPE at 0820Z on an instrument

flight plan rule for FAOR. On board were six (6) crew members, ninety four (94) passengers and two (2) live animals.

1.1.2 The departure from FAPE was uneventful, whereby the first officer (FO) was the flying pilot (FP) for this leg. During the approach to FAOR, the aircraft was cleared for landing on runway 03R. The accident occurred at approximately 1 km past the threshold. The crew stated that a few seconds after a successful touchdown, they felt the aircraft vibrating, during which they applied brakes and deployed the reverse thrust. The vibration was followed by the aircraft rolling slightly low to the left. It later came to a full stop slightly left of the runway centre line, resting on its right main landing gear and the number one engine, with the nose landing gear in the air.

1.1.3 The crash alarm was activated by the FAOR Air Traffic Controller (ATC). The Airport Rescue and Fire Fighting (ARFF) personnel responded swiftly to the scene of the accident. The accident site was then secured with all relevant procedures put in place. The aircraft sustained substantial damage as the number one engine scraped along the runway surface when the landing gear detached from the fuselage. ARFF personnel had to prevent an engine fire in which they saw smoke as a result of runway contact. The occupants were allowed to disembark from the aircraft via the left aft door due to the attitude in which the aircraft came to rest.

1.1.4 The accident occurred during daylight meteorological conditions on Runway 03R at O.R. Tambo International Airport (FAOR) located at GPS reading as: S 26°08'01.30" E 028°14'32.34" and the field elevation 5558 ft.

1.2 Injuries to persons

1.2.1 None of the aircraft occupants sustained any injuries. Two live animals were also accounted for and no injuries were noticed on either of the animals.

Injuries	Pilot	Crew	Pass	Other
Fatal	-	-	-	-
Serious	-	-	-	-
Minor	-	-	-	-
None	2	4	94	2

1.3 Damage to aircraft

1.3.1 The aircraft sustained substantial damage to the No. 1 engine as the engine scraped along the runway surface after the landing gear detached from the aircraft structure.

1.3.2 At the time the landing gear was detaching from the aircraft mountings, more damage was caused to the landing gear mounting points and mechanisms, including flaps fairings, wing root attachment fairings and the landing gear extension / retraction link (lower torsion links and shimmy damper assembly).



Figure 1: Aircraft as it came to rest

1.4 Other damage

1.4.1 Runway surface damage was caused by the landing gear during the accident sequence. There was also fuel and hydraulic fluid spillage. The runway was closed until the aircraft was recovered and all the runway surface repairs were completed.

1.5 Personnel information

Pilot-in-command (PIC)

Brief Flying History:

- 1.5.1 The Captain began her flying career in early 2000 and attained her private pilot licence in 2001 while training with Cape Aero Club. She advanced her career at all relevant levels until she attained her airline transport pilot licence on 01 November 2005. She later joined the airline transport as an aircrew. She then advanced and attained the position of Captain on the Boeing 737 series till date.

Nationality	South African	Gender	Female	Age	49
Licence Number	0270499882	Licence Type	Airline Transport		
Licence Valid	Yes	Type Endorsed	Yes		
Ratings	Instrument, Instructor grade 2, Test pilot class 2, MNPS/RVSM, A-RPN APCH				
Medical Expiry Date	30 September 2016				
Restrictions	None				
Previous Accidents	None				

Flying Experience:

Total Hours	9186.1
Total Past 90 Days	162.9
Total on Type Past 90 Days	68.2
Total on Type	2899.0

First Officer (F/O)

Brief Flying History:

- 1.5.2 The first officer began his flying career in the late 90s at 43 Air School and attained his private pilot licence on 06 September 1999. He then advanced and attained his commercial pilot licence in November 2000. In 2008 the pilot applied for aircrew membership for airline transport pilot licence examinations and attained the licence on 7 October 2009.

Nationality	South African	Gender	Male	Age	40
Licence Number	0270473556	Licence Type	Commercial		
Licence Valid	Yes	Type Endorsed	Yes		
Ratings	Instructor Grade 1, Instrument, Test pilot, class2 MNPS/RVSM, Night, A-RNP/APCH, RNP-AR-APCH				
Medical Expiry Date	30 September 2016				
Restrictions	None				
Previous Accidents	None				

Flying Experience:

Total Hours	5817.1
Total Past 90 Days	196.0
Total on Type Past 90 Days	99.2
Total on Type	480.5

1.6 Aircraft information

Airframe:

Type	Boeing 737-400	
Serial number	26960	
Manufacturer	Boeing Aircraft Company	
Year of manufacture	1993	
Total airframe hours (at time of accident)	57543.783	
Last D-Check inspection (hours & date)	48150 (CKD)	28 September 2011
Last C-Check inspection (hours & date)	55060 (CKC)	11 August 2014
Last A-Check inspection (hours & date)	57446 (CKA)	15 September 2015
Hours since last inspection CKC	2483.783	
Hours since last inspection CKA	97.783	
C of A (issue date)	11 November 2014	
C of A (expiry date)	10 November 2015	
C of R (issue date) (present owner)	10 November 2006	
Operating categories	Standard Part 121	

Engine No. 1:

Type	CFM-56-3C1
Serial number	856501
Hours since new	47 835.033
Cycles since new	32478
Hours since overhaul	TBO not yet reached at the time

Engine No. 2:

Type	CFM-56-3C1
Serial number	725274
Hours since new	59 528.500
Cycles since new	24782
Hours since overhaul	TBO not yet reached at the time

1.6.1 The Boeing 737-400 series is a low-wing, pressurised aircraft with retractable tricycle landing gear. The accident aircraft was manufactured in 1993 and operated by Comair Limited in a passenger configuration, as registered at SACAA.

1.6.2 Landing gear description

The landing gear consists of two main gears and one nose gear. Each main gear is located aft of the rear wing spar, inboard of the engine nacelles. The nose gear is located below the aft bulkhead of the control cabin. The main and nose gear use air-oil type shock struts to absorb impact on landing and vibrations and shock from movement of the airplane on the ground. Each nose and main gear is equipped with two tyre and wheel assemblies. Each main gear wheel is fitted with disc-type hydraulic brakes modulated by an antiskid system and can be controlled by an auto brake system. The main gear is hydraulically actuated to retract inboard into the fuselage. Each main gear is locked in the down position by a folding lock strut and in the up position by an up-lock hook and lock mechanism. Shock strut doors close the opening in the wing for the main gear shock strut and drag strut.

A wheel well seal closes against the main gear tyre circumference when the airplane is in flight with gear retracted. The nose gear is hydraulically actuated to retract forward into the fuselage. A lock strut assembly locks the nose gear in the up

and down positions. The clamshell-type nose gear doors close to fair with the fuselage contour when the nose gear is retracted and remain open when the nose gear is extended. The main and nose gear manual extension systems are cable-operated to release each gear from the up and locked position and allow the gear to free fall to the down and locked position. Nose wheel steering is provided for aircraft directional control during ground maneuvers. Normal steering is accomplished by using a steering wheel located at the captain's position. A reduced range of steering by rudder pedal is available.

MAIN GEAR - DESCRIPTION AND OPERATION

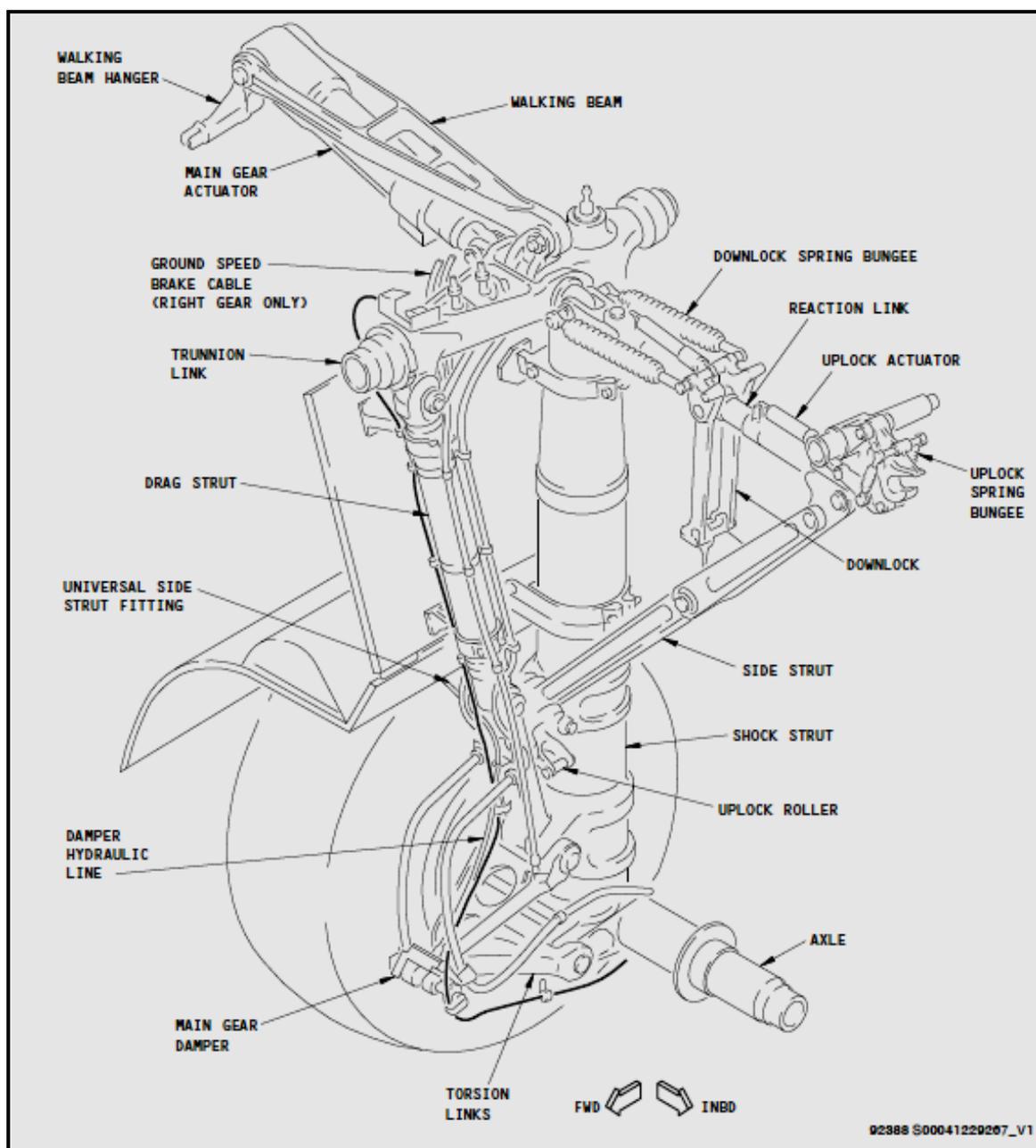


Figure 2: Main landing gear components

Each main gear consists of a trunnion link, a shock strut, a drag strut, torsion links, a damper, a side strut, and a reaction link. In addition, the right main gear carries ground speed brake-operating rods and cable. The shock strut assembly is attached to the trunnion link by a pin joint and the two are mounted between the rear wing spar and a trunnion support beam. The shock strut is charged with oil and compressed nitrogen to provide a shock absorbing medium. The main gear axles and the shock strut inner cylinder are machined from a one-piece forging. Replaceable sleeves are assembled over the axles to provide a mounting for wheel bearings and to protect the axles from damage. The reaction link is connected to the shock strut and to the upper end of the side strut.

Main Gear Trunnion Link

The main gear trunnion link provides the forward pin of the hinge for main gear retraction and transmits landing gear loads from the drag strut into the airplane structure. The trunnion link is mounted between the shock strut and the rear wing spar. The aft end of the trunnion link is pinned to the shock strut and the forward end pivots in a spherical bearing mounted in the rear wing spar. The top end of the drag strut is attached to a lug on the underside of the trunnion link near the spherical bearing. A pushrod from a bracket on the underside of the trunnion link operates a shock strut door hinged to the wing. The door covers part of the shock strut aperture in the wing when the gear retracts. A swivel fitting for hydraulic lines is mounted on top of the trunnion link. The trunnion link is machined from a high tensile steel forging. The trunnion forward-bearing bolt is designed to fail if the landing gear receives a severe impact, thus minimizing damage to structure.

Main Gear Torsion Links

The main gear torsion links prevent rotation between shock strut inner and outer cylinders without affecting the reciprocating action during normal operation of the strut. The upper torsion link and bottom attachment of the lower drag strut share the same lugs on the shock strut outer cylinder. The lower torsion link is connected to lugs on the inner cylinder. Upper and lower torsion links are joined at the forward ends by a single bolt.

Main Gear Damper

The main gear damper prevents excessive vibration buildup in landing gear during high speed taxi and under heavy braking. The damper is a hydraulic unit containing an actuator, a compensator, and relief and check valves. The main body of the damper is attached to the forward end of the upper torsion link. The actuator piston rod passes through the forward ends of both upper and lower links to provide an apex bolt. Rotary oscillation between the shock strut's inner and outer cylinders is absorbed by the actuator piston displacing hydraulic fluid in the cylinder. The rate of displacement is controlled by the damping orifice in the actuator piston. The compensator is provided to maintain a pressure of 30 to 70 psi on the fluid contained in the actuator.

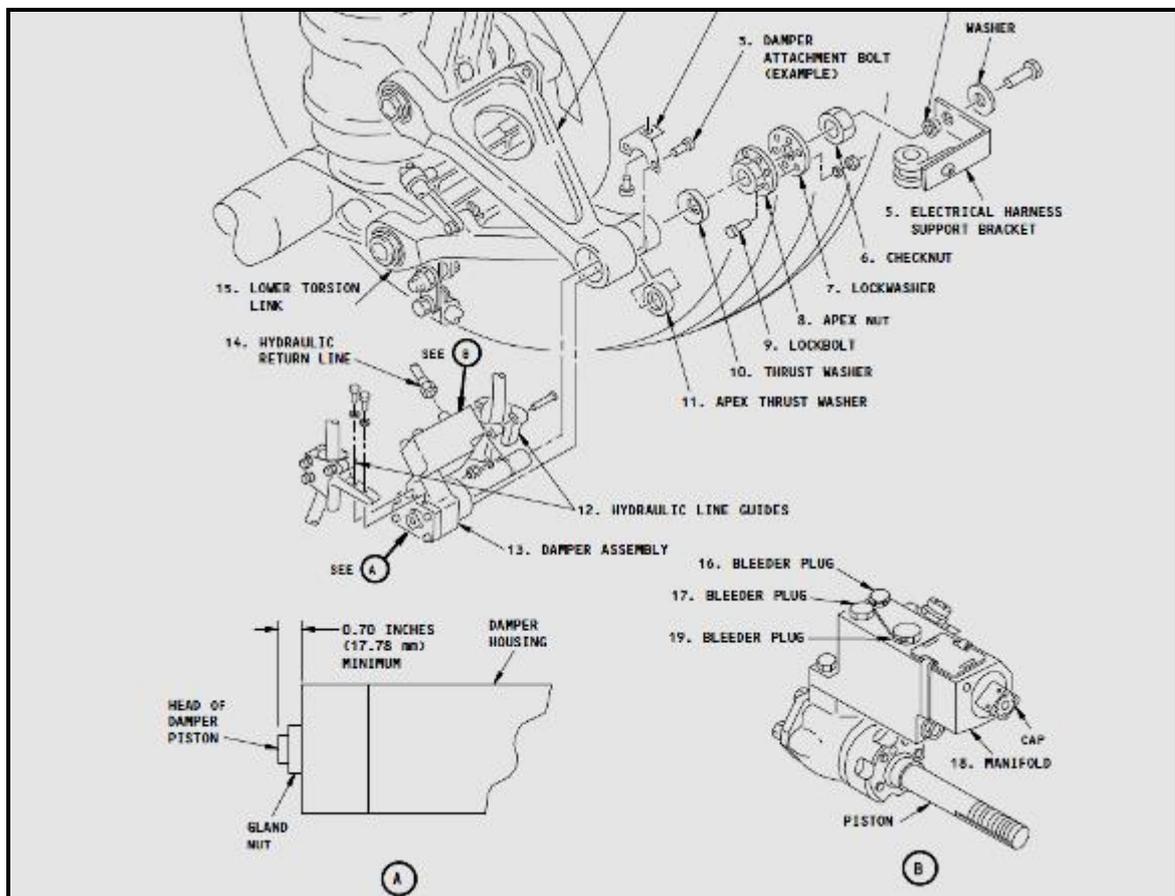


Figure 3: Main landing gear shimmy damper illustrated parts

A 3000 psi relief valve protects the actuator from very high pressures caused by thermal expansion of hydraulic fluid. A 70 psi relief valve protects the compensator from thermal expansion damage. Two check valves are provided to allow hydraulic

fluid to enter the actuator and make up for slight leakage or to compensate for fluid contraction. A third check valve permits fluid to enter the unit from the hydraulic system A return and so keeps the damper fully charged with fluid. Bleeder plugs are provided to enable trapped air to be cleared after disconnection of the hydraulic line or when filling an empty unit.

The left main landing gear (Part N: 65-737761-119; Serial N: MC05955P2586) was shipped in November 2010 and was installed on the aircraft in the same year (December), following the overhaul maintenance at 27898 cycles. The table below provides a list of the affected parts during the accident sequence.

Landing Gear Part description	Part Number	Serial Number	Life Limit Cycles	Cycles at Initial Installation	Cycles at Time of Accident	Life Remaining
Left Main Gear Assembly	65-737761-119	MC05955 P2586	75000	27898	35470	39530
Upper Torsion Link	65-67963-4	5892	75000	41337	48909	26091
Lower Torsion Link	65-46102-24	SS142	75000	34925	42497	32503
Shimmy Damper	65-44771-4	TSC2351-	Unlimited	Unlimited	Unlimited	Unlimited

1.6.3 Airplane General Limitations

The information is extracted from the Boeing 737-300/-400/-500 Operations Manual: Revision Dated: December 06, 2002

Runway Slope	+/-2%
Maximum Take-off Landing Tailwind Components	10 knots
Maximum Speed	Observe Vmo pointer and gear/flap placards
Turbulent Airspeed	280 KIAS/.73M
Maximum Flight Operational Latitude	73° North and 60° South
Maximum Flight Operational Altitude	37,000 feet (ft)
Maximum Take-off and Landing Altitude	8,400 feet (ft)

Weight Limitation

Maximum Taxi Weight	139 000 lbs (63 049 kgs)
Maximum Take-off Weight	138 500 lbs (62 822 kgs)
Maximum Landing Weight	121 000 lbs (54 844 kgs)
Maximum Zero Fuel Weight	113 000 lbs (51 255 kgs)

(C.G Limits) use of approved weight and balance system

According to the weight and balance calculation made for this specific flight, the aircraft weight and balance was within limits, with enough fuel on board.

Landing Gear Limitations

Non-AFM Landing Gear Operational Information

Note: The following item does not form part AFM limitations but are provided for flight crew information.

Do not apply brakes until after touchdown

- 1.6.4 According to the maintenance procedures on the landing gear, the maintenance carried out on the shimmy damper involves visual inspection for fluid leak check and adjustment. In reference to all the records, the shimmy damper has an unlimited lifespan. Aircraft documentation – maintenance records, certificates and service bulletin letters – were studied and reviewed. According to these, the aircraft had been equipped and maintained according to existing regulations. All service bulletins published by the engine and aircraft manufacturers had been adhered to and complied with by both the owner and aircraft maintenance organisations (AMOs).

1.7 Meteorological information

- 1.7.1 Meteorological information as obtained from the South African weather service website:

Wind direction	034°	Wind speed	10 kt	Visibility	9999
Temperature	26°C	Cloud cover	FEW	Cloud base	4500 ft
Dew point	04°C				

1.8 Aids to navigation

- 1.8.1 The aircraft was equipped with the following navigational aids:

- (i) Very High Frequency Omni-directional Radio Range (VOR)

- (ii) Automatic Direction Finding (ADF)
- (iii) Instrument Landing System (ILS)
- (iv) Distant Measuring Equipment (DME)
- (v) Transponder
- (vi) Global Positioning Systems (GPS)

There was no reported defect regarding any of the navigational equipment.

1.9 Communication

1.9.1 The aircraft was in radio communication with air traffic control (ATC) at O.R. Tambo International Aerodrome on the VHF frequency 118.10 MHz. There was no reported defect during flight.

1.10 Aerodrome information

1.10.1 The aircraft landed on runway 03R at O.R. Tambo International Aerodrome.

Aerodrome location	Gauteng Province at FAOR	
Aerodrome co-ordinates	S 26°08'01.30" E 028°14'32.34"	
Aerodrome elevation	5 558 feet above mean sea level (AMSL)	
Runway designations	03L/21R	03R/21L
Runway dimensions	4 421 x 60 m	3 405 x 60 m
Runway used	03R	
Runway surface	Asphalt	
Approach facilities	ILS, DME, VOR, PAPI's, Runway lights	
Aerodrome status	Licensed	

1.11 Flight recorders

1.11.1 The aircraft is equipped with a flight data recorder (FDR) and a cockpit voice recorder (CVR). Both these units were removed from the aircraft for further investigation.

1.11.2 The aircraft was also equipped with a quick access recorder (QAR) (Refer to: Annex

B). This device records the same data as the FDR. The FDR (P/N: 980-4120-DXUN; S/N: 7197) data analysis indicated the following readings as assisted by the state of manufacture, which was the same as the data analysis at the local data analysis facility downloading lap at SAT:

- Airplane touched down at 139 knots computed airspeed (VREF+6) and at 167 knots ground speed
- The sink rate at touchdown was approximately 2 feet/second, and the touchdown normal load factor was around 1.1 g. These are not characteristics of a hard landing
- The airplane had an approximate 2-3 degree left bank angle and a 1 degree right drift angle at touchdown
- The left main gear collapsed as the airplane completed de-rotation
- Wheel brakes were applied immediately following touchdown, although it was unclear whether it was manual or autobrake.

1.11.3 The CVR (Pat N: 980-6022-001; S/N: 1732) data recordings revealed that all landing checklist procedures were followed in accordance with the pilot operating procedure handbook manual for the aircraft type.

1.12 Wreckage and impact information

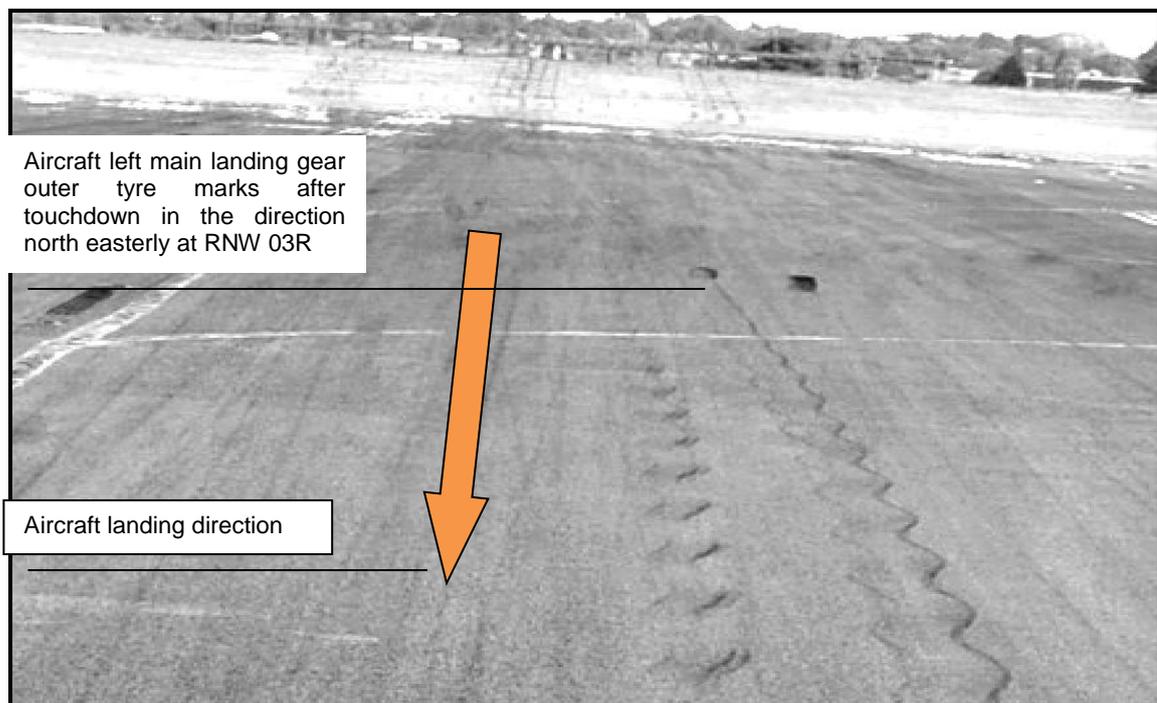


Figure 4: Shows initial contact marks

1.12.1 The accident occurred during landing on a cleared runway 03R. The on-site observation was that, during landing, the aircraft was subjected to a slight left roll attitude which might have enabled the aircraft to make contact with the runway with the left main landing gear first. It is not clear where the aircraft initially touched down, but at approximately 1 km past the threshold, the left main landing gear tyre marks indicated a form of shuddering manoeuvring beginning slightly and increasing gradually. This was inconsistent with the pilot's statement that during touchdown the aircraft started vibrating.



Figure 5: Shows the left-hand side landing gear tyre marks as it wiggled

1.12.2 The aircraft's left-hand main landing gear shuddering tyre marks occurred for a distance of approximately 200 m, whereby the runway surface damage was observed at the same place where the No.1 engine began scraping along the runway surface. At this time the left main landing gear had collapsed and was dragged along, causing the left wing to drop. There was evidence of runway surface damage at three intervals of approximately 1.7 m apart, appearing together with the hard tyre contact marks. The damage was consistent with damage caused by the outer wheel tyre assembly as it was dragged along. The damage on both wheel tyres was consistent with damage caused by an object that punched through at the same level with the upper broken torsion link. This may also indicate that both tyres were damaged after the shimmy damper bolt failed and the oscillations were

occurring.

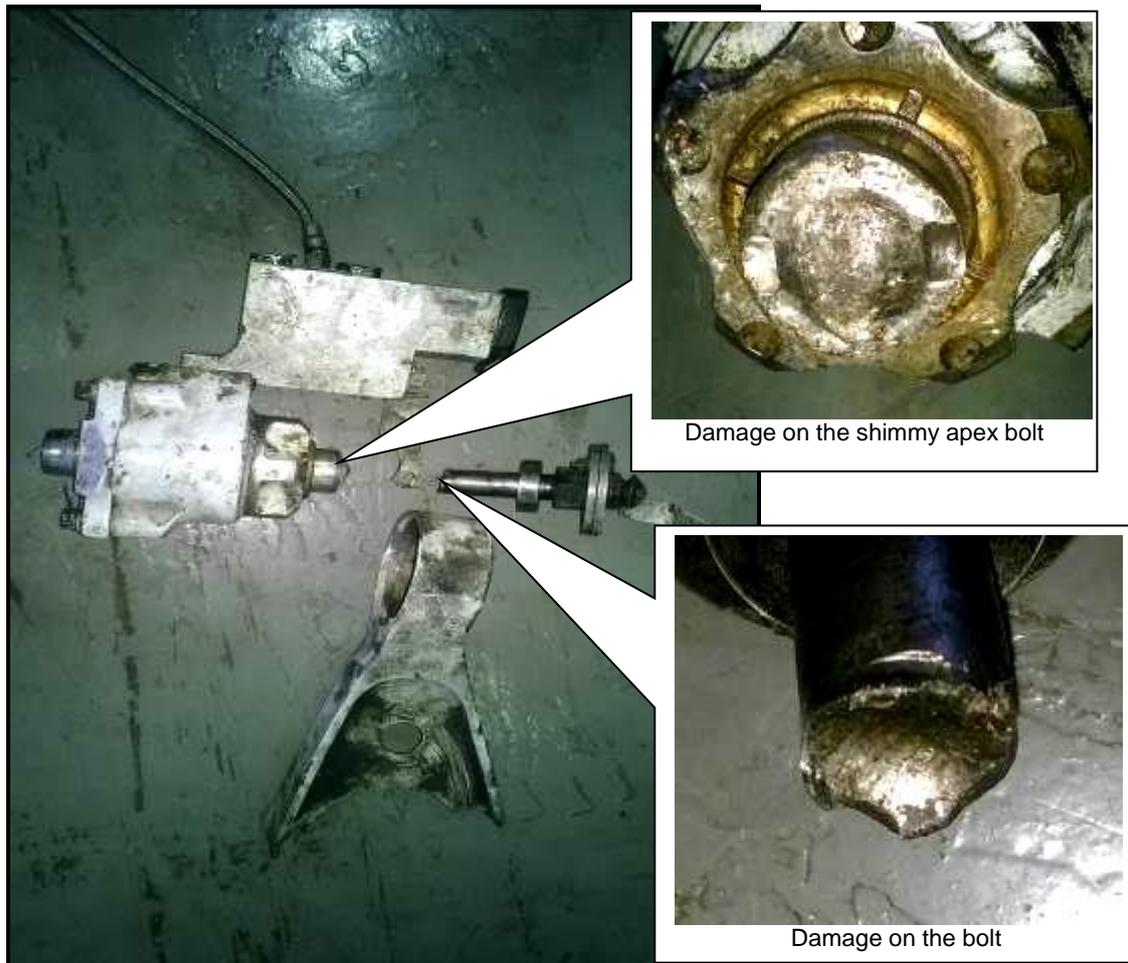


Figure 6: Damage on the shimmy damper component

1.12.3 . There was also evidence of some runway damage which was consistent with the damage caused by the shimmy damper component prior to detaching from the upper torque-link as the landing gear was dragged along. The shimmy damper was found on the left side lying a few metres from the landing gear extension / retraction mechanical actuator, just after the main landing gear doors debris. About several metres away there was an upper torsion link piece of a broken torsion link which connects directly to the shimmy damper. The damage on the shimmy damper is consistent with a component which was subjected to excessive tensile force.

1.12.4 The damage to the trailing edge of the left wing, towards the wing root, was caused by the landing gear as it detached from the main assembly points. The inner flaps were also damaged by the landing gear. The trunnion forward-bearing bolt is designed to fail if the landing gear receives a severe impact. The observations revealed that the fuse lugs on the trunnion link gave a positive reaction characteristic with regard to design failure as it prevented damage to the left wing

tanks during the accident sequence.



Figure 7: Shows damage on the trailing edge flaps



Figure 8: Landing gear



Figure 9: Shows the wreckage trail and accident sequence

1.12.5 The wreckage debris was scattered along the runway length during the accident sequence. There was further visible runway surface damage caused by the left landing gear assembly as it moved towards the left side of the runway. The left landing gear was violently detached from the airframe assembly points, and came

to a complete stop approximately 1.7 km from the threshold during the accident sequence.

1.13 Medical and pathological information

1.13.1 Not applicable. No medical attention was required at the accident site.

1.14 Fire

1.14.1 During the scraping of the No.1 engine (left side) an engine warning initiated. The pilot in command pulled the No.1 engine fire handle, once the aircraft had come to a stop, to cut fuel and hydraulic supply to the engine. On arrival the aerodrome rescue and fire-fighting (ARFF) personnel responding to the accident immediately observed the fire smoke and proceeded to extinguish it.

1.15 Survival aspects

1.15.1 This was considered a survivable accident. None of the occupants, including two live animals, sustained injury or mental shock during the accident sequence.

1.16 Tests and research

1.16.1 The failed upper torsion link and the shimmy damper components were shipped to the National Transport Safety Board Laboratory at Washington DC in the United States of America for failure analysis test. Damage assessment inspection was carried out on the components prior to preparing for laboratory tests. (1) The hydraulic tests for both the shimmy damper and its compensator were carried out. (2) The components were later disassembled for inspection. For the full component test report please refer to Annex B.

BACKGROUND:

It was reported that on October 26, 2015, during the landing rollout, the left main gear collapsed and departed the aircraft.

SUMMARY:

Examination and testing of the subject shimmy damper and associated parts were performed in the Boeing Equipment Quality Analysis (EQA) lab in Seattle on May 10, 2016. During the testing, the damper failed a step of the hydraulic functional tests. This failure was indicative of a condition that would have impaired damper function and thus may have been a contributing factor to the shimmy event. An attempt was made to isolate the faulty component within the damper. Testing showed that the thermal relief valve within the damper had intermittent internal leakage, which was causing the test failure. In addition to the hydraulic failure, significant wear was found on the upper torsion link bushings. Wear in these areas can also be a contributing factor to shimmy, since the wear allows undamped torsional free play of the landing gear.

- 1.16.2 Based on the information provided regarding the accident site wreckage mapping and the flight data recording (FDR) information, the following discussion was established by the National Transport Safety Board (NTSB).

Shimmy Event Discussion

At the time of writing, there had been no confirmation that the main landing gear had collapsed due to a shimmy oscillation. However, the characteristics of the landing are consistent with past landing-gear shimmy events. The airplane touched down at a high ground speed and low sink / closure rate. The air / ground discrete transition to GROUND occurred approximately one second after touchdown, indicating that the struts were extended for that period of time. As a result, the torsion links of the shimmy damper remained in an extended, vertical position, where the damper has less mechanical advantage for longer periods of time.

Preventing the Shimmy Events

Information is extracted from AERO QTR_03, 13 The Boeing Edge

Based on operator reports, MLG shimmy is an infrequent event that is characterised by strong vibration, usually from one MLG, that begins at touchdown and continues until the airplane is fully stopped. Historically, there have been two or three shimmy

events a year in the worldwide 737-200/ -300/-400/-500 fleet. However, in the last few years, the rate of shimmy events has increased sharply on these models. In a few particularly severe shimmy events, the affected main landing gear collapsed during the landing. This article discusses causes of shimmy and recommended actions operators can take to reduce the likelihood of it occurring. Boeing sometimes receives reports from operators of what is assumed to be a hard landing because of the violent nature of the landing and the observation of a torsion link fracture.

However, Boeing's experience with these landings reveals that such damage actually suggests a shimmy event occurred. Despite the presence of shimmy damper hardware, which is attached to the apex lugs on each MLG and is designed to reduce the torsional vibration energy generated during landing, airplanes occasionally experience MLG shimmy. Shimmy events almost always result in damaged torsion links and shimmy dampers. When a torsion link is completely severed, it can leave oscillating tyre marks on the runway. Following a shimmy event, the airplane typically needs to be temporarily removed from revenue-generating service for inspections and repairs. The Aero Magazine article concludes with the following:

- *Due to the geometry of the torsion links, the shimmy damper is most effective when the landing gear strut is compressed in the ground mode. Lower touchdown descent rates increase the likelihood of a shimmy damper failure. It is important to note, however, that proper maintenance of the gear components is the best way to prevent shimmy damper failures. The possibility of landing gear shimmy events is greater at high altitude airports. (Refer to Figure 10 below for illustration)*

Boeing also recommends that pilots strive for a landing with normal sink rates with particular emphasis on ensuring that the auto speed brakes are armed and deploy promptly at touchdown. An overly soft landing, or a landing in which the speed brakes do not promptly deploy, allows the landing gears to remain in the air mode longer, which makes them more vulnerable to shimmy. This is especially true when landing at airports located at higher elevations, where the touchdown speed is increased.

During final approach, flare was initiated early at a radio altitude of approximately 65 feet, which is higher than the recommended 20 feet. The early flare initiation contributed to the airplane float that led to touchdown at a low sink rate.

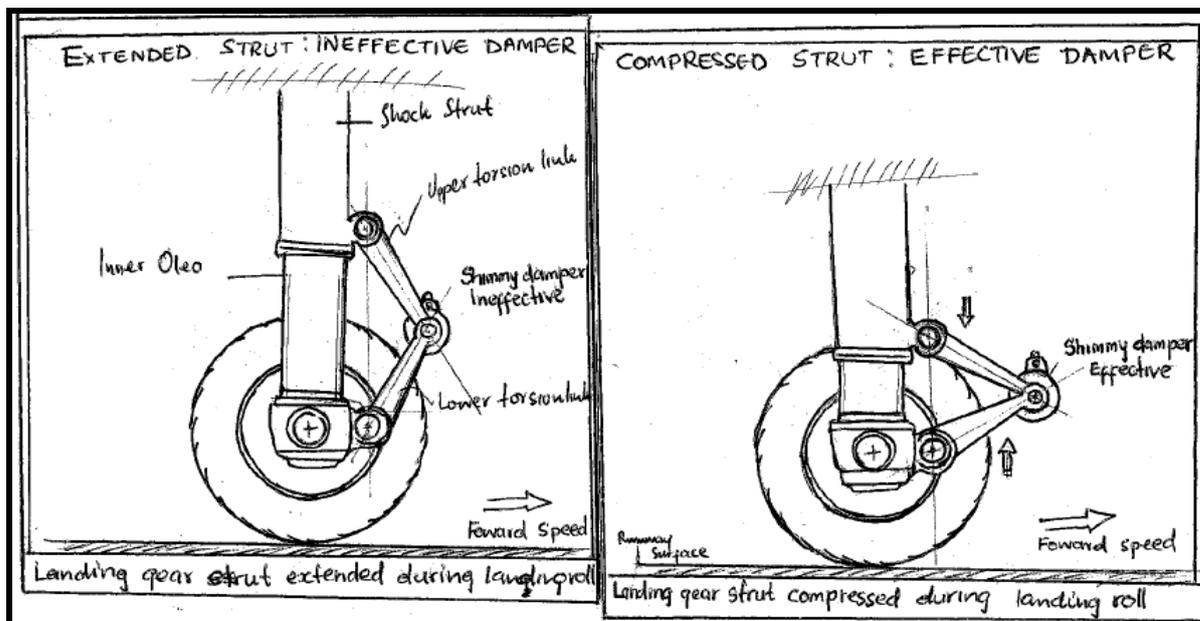


Figure 10: Demonstrate the conditions of extended and compressed strut during landing

Note: Figure 10 above is used for illustration of the geometric of the torsion links as discussed above with regard to the effectiveness of the shimmy damper with given conditions during landing roll phase.

Conclusion

A manual approach was performed by the crew that was determined to be unstable, based on the stabilized approach criteria. A combination of a tailwind and high approach speed, while landing at a high altitude airport, resulted in excessive ground speed (167 knots) at touchdown. An extended flare that was the result of an early flare initiation led to touchdown at a low sink rate (1.8 feet/second). The left main gear collapsed approximately 5 seconds after touchdown, and the airplane came to a stop around 35 seconds later. Although the official investigation has not determined the cause of the landing gear collapse, prior service experience on the 737 has shown that touchdown at high ground speeds and low sink rates increases the likelihood of the initiation of main gear shimmy. Prior service history on the 737 has shown that gear collapse is a possible outcome of shimmy.

Note: The full test results are provided as Annex B attachment for reference.

1.17 Organisational and management information

1.17.1 This was a domestic commercial flight conducted under the guidance of Part 121 of the Civil Aviation Regulations of South Africa.

1.17.3 The operator was a holder of a valid AOC attained with the approved regulatory procedures, which was to expire on 28 April 2016.

1.17.4 The aircraft was maintained by the regulator-approved AMO in accordance with the manufacturer's approved procedures. The AMO holds a valid AME certificate attained from the regulator in accordance with existing regulations, which was due to expire on 31 October 2015.

1.17.5 Following the ZS-OAA accident, the operator (Comair) decided to inspect their remaining fleet of thirteen 'classic' B737s (300/400) as per terms of Service Letter SL: 737-32-057D.

No defects were found during the shimmy damper torsion link apex joint inspection.

1.18 Additional information

1.18.1 Operational Guidance

Stabilized Approach Assessment

The following statements were extracted from the reference (c) 737 CL Flight Crew Training Manual with regard to the Flight Safety Foundation's published criteria for flying a stabilized approach. It recommends that a go-around should be initiated if the approach becomes unstabilized under 1000 feet above the ground for instrument meteorological conditions and under 500 feet for visual meteorological conditions.

Stabilized Approach Recommendations

Maintaining a stable speed, descent rate, and vertical/lateral flight path in landing configuration is commonly referred to as the stabilized approach concept.

Any significant deviation from planned flight path, airspeed, or descent rate should be announced. The decision to execute a go-around is not an indication of poor performance.

Note: *Do not attempt to land from an unstable approach.*

Recommended Elements of a Stabilized Approach

The following recommendations are consistent with criteria developed by the Flight Safety Foundation.

All approaches should be stabilized by 1,000 feet AFE in instrument meteorological conditions (IMC) and by 500 feet AFE in visual meteorological conditions (VMC). An approach is considered when all of the following criteria are met:

- the airplane is on the correct flight path
- only small changes in heading and pitch are required to maintain the correct flight path
- the airplane should be at approach speed. Deviations of +10 knots to – 5 knots are acceptable if the airspeed is trending toward approach speed
- the airplane is in the correct landing configuration
- sink rate is no greater than 1,000 fpm; if an approach requires a sink rate greater than 1,000 fpm, a special briefing should be conducted
- thrust setting is appropriate for the airplane configuration
- all briefings and checklists have been conducted.

Specific types of approaches are stabilized if they also fulfil the following:

- ILS and GLS approaches should be flown within one dot of the glide slope and localizer, or within the expanded localizer scale
- approaches using IAN should be flown within one dot of the glide path and FAC
- during a circling approach, wings should be level on final when the airplane reaches 300 feet AFE.

Unique approach procedures or abnormal conditions requiring a deviation from the above elements of a stabilized approach require a special briefing.

Note: An approach that becomes unstabilized below 1,000 feet AFE in IMC or below 500 feet AFE in VMC requires an immediate go-around.

These conditions should be maintained throughout the rest of the approach for it to be considered a stabilized approach. If the above criteria cannot be established and maintained until approaching the flare, initiate a go-around.

At 100 feet HAT for all visual approaches, the airplane should be positioned so the flight deck is within, and tracking to remain within, the lateral confines of the runway edges extended.

As the airplane crosses the runway threshold it should be:

- stabilized on approach airspeed to within +10 knots until arresting descent rate at flare
- on a stabilized flight path using normal maneuvering

- positioned to make a normal landing in the touchdown zone (the first 3,000 feet or first third of the runway, whichever is less).

Initiate a go-around if the above criteria cannot be maintained.

Maneuvering (including runway changes and circling)

When maneuvering below 500 feet, be cautious of the following:

- descent rate change to acquire glide path
- lateral displacement from the runway centerline
- tailwind or crosswind components
- runway length available.

Below 1000 feet radio altitude, the airplane did not adhere to three of the above recommended stabilized approach criteria. These criteria are summarized below:

- the airplane is on the correct flight path. The recorded glideslope deviations indicate the airplane was above the intended glide path.
- the airplane should be at approach speed. For a tailwind approach, the recommended approach speed (VAPP) is VREF+5, which in this case was 138 knots. On average, computed airspeed was 148 knots (VAPP+10) but reached as high as 154 knots (VAPP+16) prior to flare, which exceeded the allowable deviation above approach speed by 6 knots (10 knots is allowed).
- sink rate is no greater than 1000 fpm. Throughout the approach, there were several sink rate exceedances of 1000 fpm.

Flare Guidance

The Flight Crew Training Manual also contains the following recommendations that are applicable to this event:

Initiate the flare when the main gear is approximately 20 feet above the runway by increasing pitch attitude approximately 2° - 3°. This slows the rate of descent.

After the flare is initiated, smoothly retard the thrust levers to idle, and make small pitch attitude adjustments to maintain the desired descent rate to the runway. A smooth thrust reduction to idle also assists in controlling the natural nose-down pitch change associated with thrust reduction. Hold sufficient back pressure on the control column to keep the pitch attitude constant. Ideally, main gear touchdown should occur simultaneously with thrust levers reaching idle.

Do not allow the airplane to float or attempt to hold it off. Fly the airplane onto the runway at the desired touchdown point and at the desired airspeed.

Prolonged flare increases airplane pitch attitude 2° to 3°. When prolonged flare is coupled with a misjudged height above the runway, a tail strike is possible. Do not

prolong the flare in an attempt to achieve a perfectly smooth touchdown. A smooth touchdown is not the criterion for a safe landing.

1.19 Useful or effective investigation techniques

1.19.1 No new methods were applied.

2. ANALYSIS

2.1 Man

2.1.1 The flight crew was licensed, well equipped and qualified for the flight in accordance with existing regulations.

2.1.2 The actions and statement of the First Officer, who was flying the aircraft, indicate that his knowledge and understanding of the aircraft system were adequate. No negative operational factor which could have contributed to this accident was noticed during investigation.

2.2 Machine

2.2.1 The aircraft was certified, equipped and maintained in accordance with existing regulations and approved procedures. The aircraft had a valid Certificate of Airworthiness at the time of the accident, and it was attained in compliance with the existing regulations.

2.2.2 During post-investigation the following were revealed from the Flight Data Recorder analysis and the components failure tests / analysis.

- According to the recordings of the FDR, the aircraft had an early flare initiated at 65 ft AGL, as compared to the recommended 20ft AGL. This resulted in the aircraft floating and caused a low rate of descent during landing touchdown. The forward touchdown speed was also high, at 167 kt.

This condition was induced with the good intention of achieving a smooth landing touchdown, but it had a negative impact on the landing gear shimmy

effectiveness. According to Boeing the low sink rate during landing touchdown increases the likelihood of shimmy damper failure. Due to the geometry of the torsion links, the shimmy damper was less effective during a prolonged touchdown roll with the main gear strut in an extended position. This might have allowed the torsional forces to effect damage to the upper torsion link. The upper torsion link had a remaining lifespan of approximately 26091 landings, of its total expected lifespan of 75000 landings. It is also possible that the torsion link had already lost its maximum strength during the cause of the life it had already spent in operation. At the time of landing, due to the excessive vibration which was not damped at the time, the strut was still extended, the torsion link failed at its weakest design material strength.

- The shimmy damper also failed a step during tests in which oil was found in the thermal relieve valve. The presence of the oil could have hampered the effectiveness of the shimmy damper. This shows that there had been an internal leak over a long period. This could have been due to the inner seals damage, which was noticed during disassembling of the components following test failure.

During the wheel brakes application, the shimmy damper might have also been less effective, due to the impaired damper failure. The shimmy damper works most during initial touchdown and during brake application.

- Also, according to the test results, significant wear was found on the upper torsion link's bushing and the flanges. Although the wear was not far beyond limits it could also play a role due to undamped vibrations continuing to increase shimmy events.

The three above-mentioned findings, merged together, can play a significant role in inducing the shimmy events that led to this accident. From the wreckage distribution it is evident that the upper torsion link failed first, allowing the shimmy damper attached to the remaining parts that link to the bottom torsion link to drop during wheel oscillation. This played a significant role in a complete landing gear failure. The shimmy damper detached as it sustained damage during the impact sequence, as the main landing gear became detached from the main attachment points. The landing gear detached as per the design fail safe system, which prevents damage on the wings main spar. Should it be that the main spar damaged and affected the fuel tank, there was a high chance of fire erupting during the accident sequence,

due to the running engine and the possible heat generated from impact friction with the runway surface. The results could have been catastrophic.

2.2.3 According to the maintenance details prescribed for the aircraft maintenance organisation (AMO) on the shimmy damper, it does not involve overhaul. It is in most cases based on condition; however, the AMO do not have overhauling capabilities. Should it be that during the main landing-gear overhaul, the shimmy damper's test and condition remain serviceable, the shimmy damper is reinstalled and it continues in operation. The shimmy damper component has an unlimited life span, unless it is certified unserviceable due to its ineffectiveness during operational tests. Also, in most inspections carried out, AMO personnel only look out for external fluid leaks and wear bushing. The shimmy damper was found with an internal leak during the laboratory tests following the accident.

On the basis of the service history, the investigation concludes that the damage to the shimmy damper seal was sustained during assembly on the last overhaul.

2.3 Environment

2.3.1 O.R. Tambo International Airport is at an altitude of 5558 ft above sea level and the pressure altitude of the airport at the time of landing was approximately 5100 ft. The wind was from of a south-southwest direction at approximately 5 kt, increasing to 15 kt prior to touchdown. There was a predetermined tailwind component heading at 34 degrees at 10 kt during touchdown. The effect of the tailwind prolonged the landing roll, but the runway length was sufficient to execute a safe landing in the existing wind conditions.

2.3.2 It is every pilot's desire to execute a safe smooth landing for passenger comfort and aircraft sustainability. These skills are acquired with flying experience. They also are regulated by the environmental conditions at the time of the flight. The technique differs from one operating aerodrome altitude to another, due to pressure altitude and latitude conditions. The aircraft flaring was initiated at an earlier stage at approximately 65 ft AGL as compared to the recommended 20 ft (AGL).

According to the FDR, the pitch angle was correct, but the pilot allowed the airplane to float or attempted to hold it off. When prolonged flare is attempted to achieve a perfectly smooth touchdown, the aircraft is at risk of landing gear torsion link failure,

due to ineffectiveness of the shimmy damper as the landing gear remains extended for a long period of time.

2.4 Operation

2.4.1 The flight was conducted in accordance with approved procedure in the company's Operational Manual. The flight crew carried out a normal radio communication with the relevant ATC at the time of approach and during landing execution.

3. CONCLUSION

3.1 Findings

3.1.1 The aircraft crew was qualified, licensed and equipped for the operation in accordance with existing regulatory procedures.

3.1.2 The flying pilot at the time was medically fit to conduct the flight with sufficient experience on the aircraft type.

3.1.3 The aircraft had a valid Certificate of Airworthiness, which was attained in accordance with approved procedure.

3.1.4 The aircraft weight and balance were within limits.

3.1.5 According to the FDR recordings, the aircraft flare was initiated earlier at 65ft than at 20ft as recommended by aircraft manufacture, which contributed to the low sink rate.

3.1.6 The shimmy damper failed the post-accident lab-test and fluid was found in the thermal relief valve, which could have contributed to the shimmy damper failure.

3.1.7 According to the lab results, significant wear was found on the upper torsion link bushing and flange, which could have contributed to undamped vibration continuation.

3.1.8 The aircraft had a tailwind component during landing, which could have prolonged the landing distance.

3.19 The aircraft touchdown was at a high forward speed.

3.2 Probable Cause/s

3.2.1 Unstable approach whereby the aircraft was flared too high with high forward speed resulting with a low sink rate in which during touch down the left landing gear experienced excessive vibration and failed due to shimmy events.

4. SAFETY RECOMMENDATIONS

4.1 The aircraft manufacturer (Boeing) has taken a safety action by publishing The Safety Issued Magazine AERO QTR_03, 13 The Boeing Edge: It is recommended that the Boeing consider the review of Aircraft Operations Manual and / or issue a safety bulletin in light of the findings contained in the Safety Issued Magazine.

4.2 The safety action taken by the operator:

(a) Pilot's notice was issued informing pilots of the potential gear shimmy and failure problem during high-speed and soft landings.

(b) Ordered that all operator's fleet of B737-400 be inspected in order to establish further potential excessive wear and more regular inspections have been scheduled (over-and-above Manufacturer's requirements) in order to monitor the fleet going forward.

5. APPENDICES

5.1 Annex A: Operational Guidance

5.2 Annex B: FDR Analyses

5.3 Annex C: Comair Comments

5.1 Annex A: Components Failure Tests

EXAMINATION AND TEST RESULTS:

On May 10, 2016, an analysis was performed at the Boeing Company in Seattle, Washington on the main gear damper assembly.

The parts delivered to the Boeing Equipment Quality Analysis (EQA) group by the NTSB representative were photographed as received; see Figure 1 through to Figure 4.



Figure 1



Figure 2



Figure 3

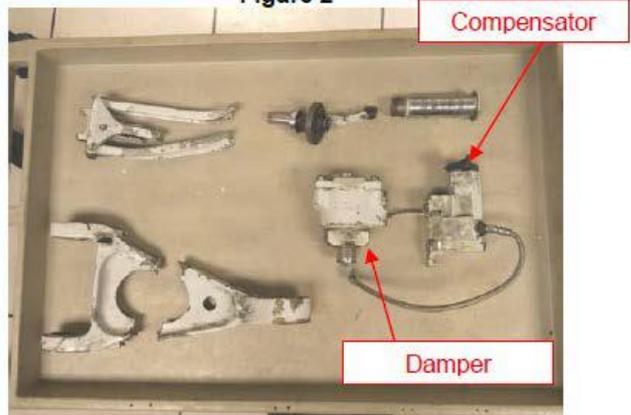


Figure 4

The main gear damper assembly was identified by the part number and serial number that were provided by the aircraft operator. There was no identification tag on the damper assembly.

Initial examination showed that the damper assembly was separated into two sections, as seen in Figure 4. Figure 5 shows the main gear damper assembly in its normal assembled configuration.

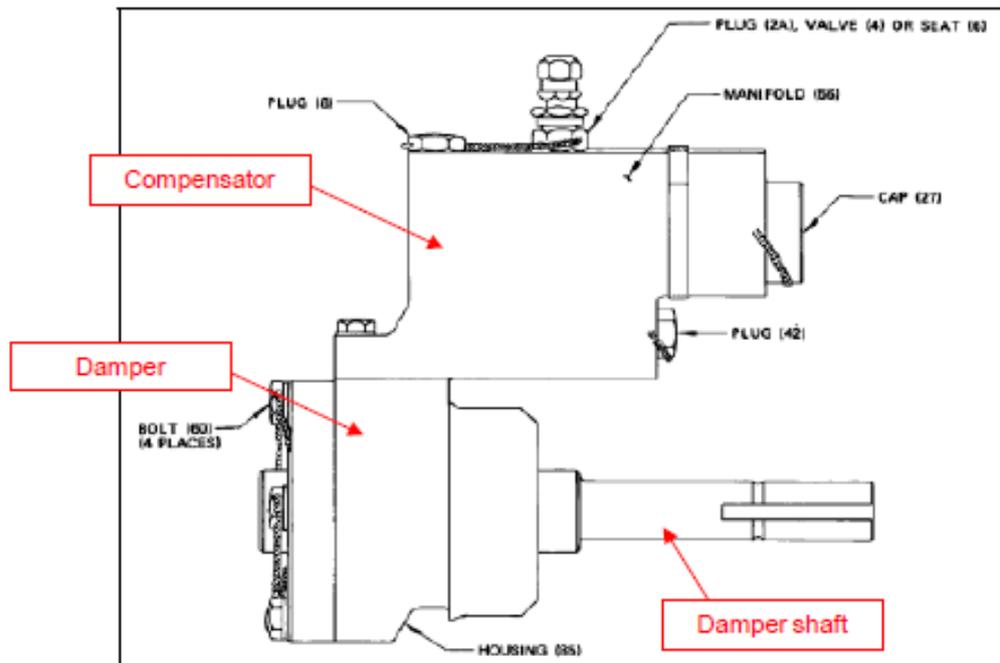


Figure 5 – Excerpt from Reference (a)

The general exterior condition of the parts displayed damage from the event. All of the five attachment bolts that secure the damper assembly to the torsion link were fractured, and portions of the bolts were still in the attachment holes; see Figure 6.

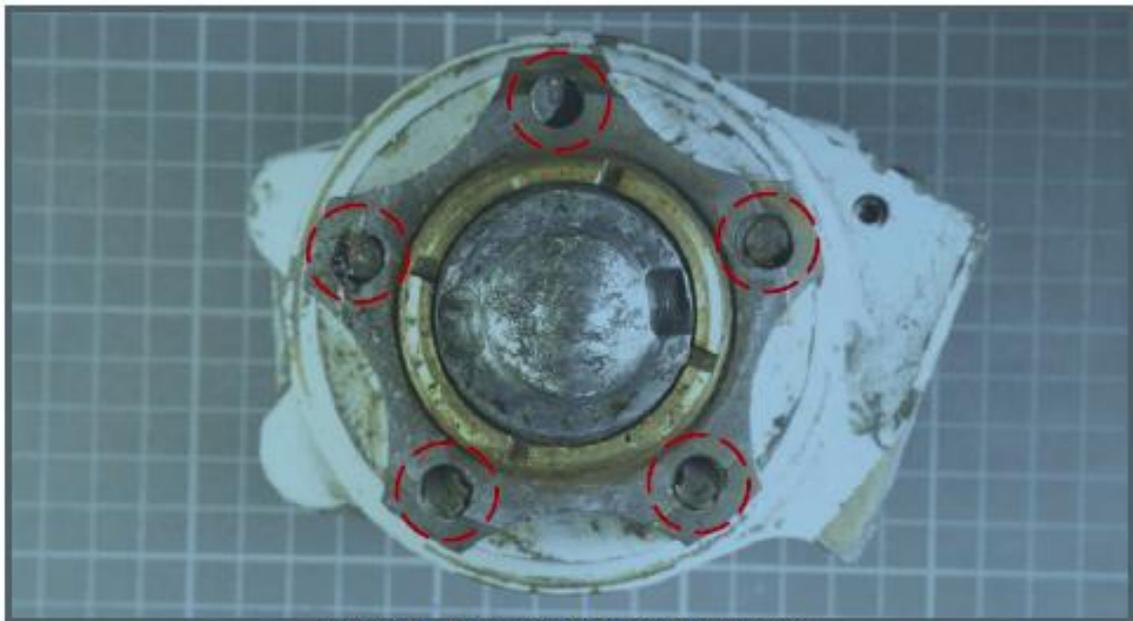
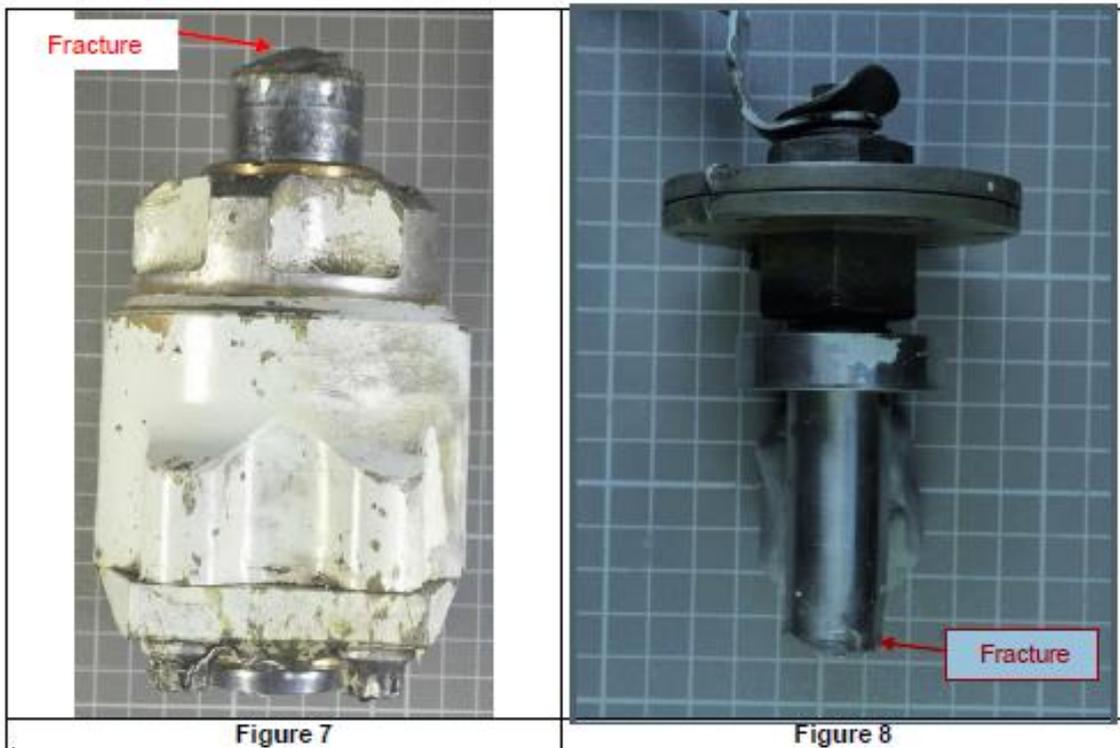
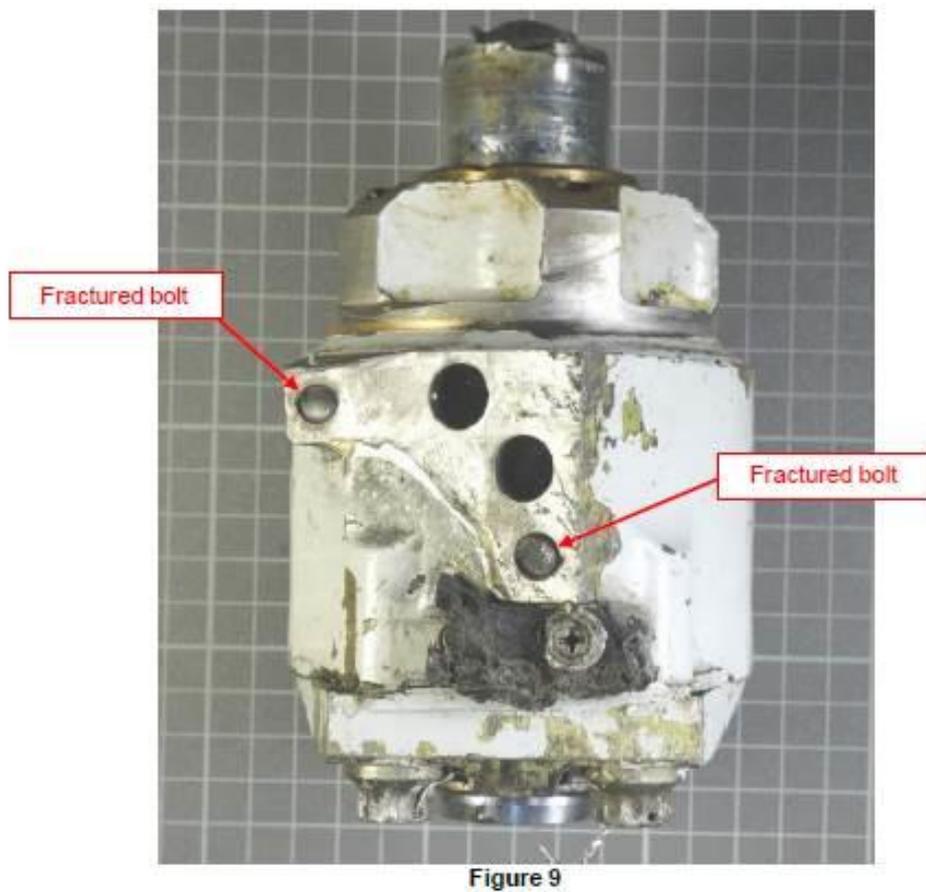


Figure 6 – Fractured bolts encircled in red

The damper piston shaft was fractured, and a portion of it was separated from the main portion that was still in the damper housing; see Figure 7 and Figure 8.



The two bolts that mount the compensator and damper together were fractured, and portions of the two bolts were still in the attachment holes; see Figure 9.



Neither of the two transfer tubes, between the compensator and damper, was present; see Figure 10 and Figure 11.



Figure 10



Figure 11

A mounting bracket was still attached to the compensator with a bolt; see Figure 12 and Figure 13. Also seen in Figure 12 is that a portion of the compensator housing, containing one of the bolt holes, had fractured off and was missing.

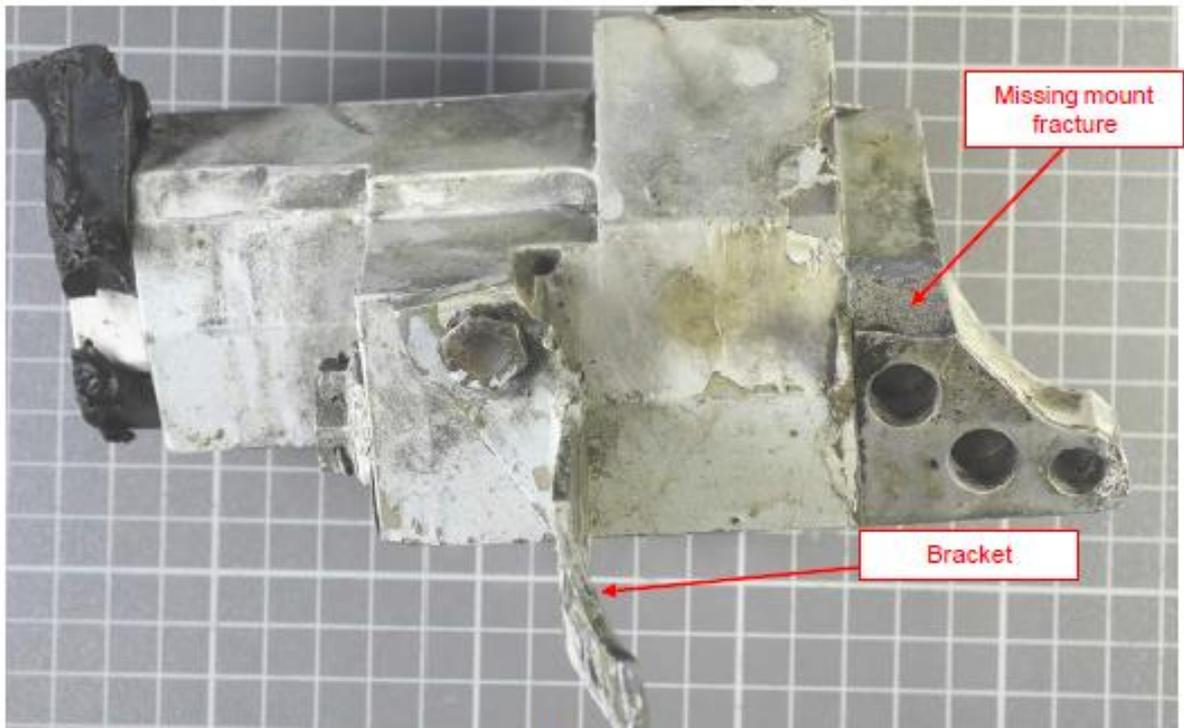


Figure 12

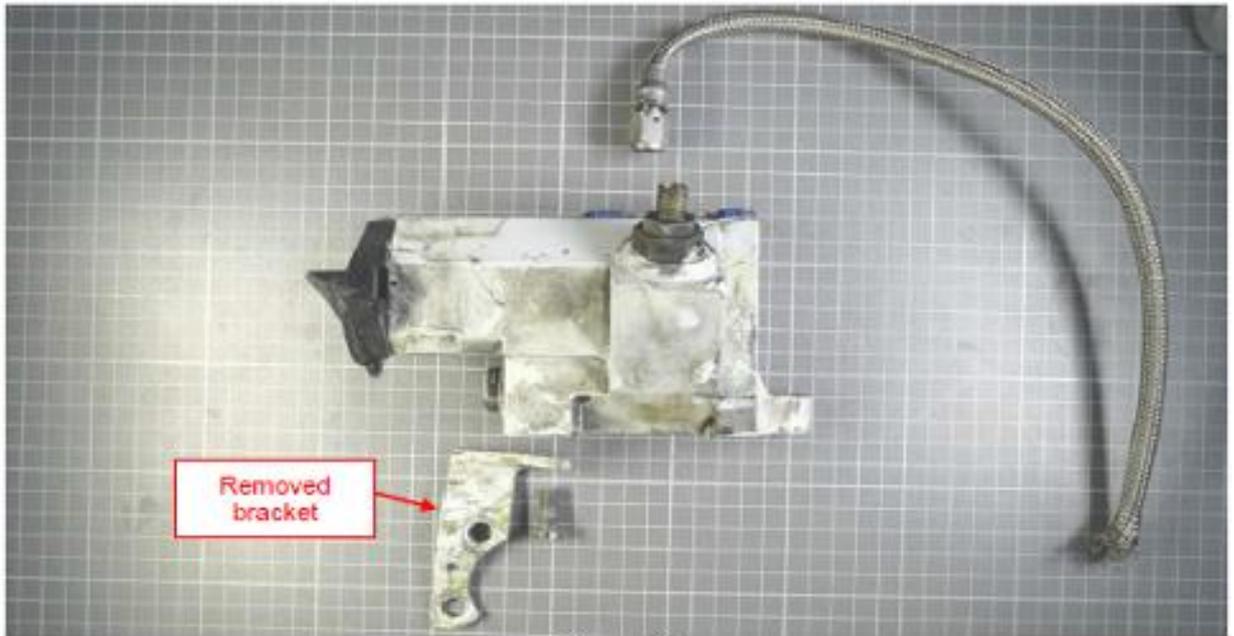


Figure 13

The compensator portion of the damper assembly was analysed using digital radiography (DR) imaging; see Figure 14 and Figure 15. No anomalies were found.

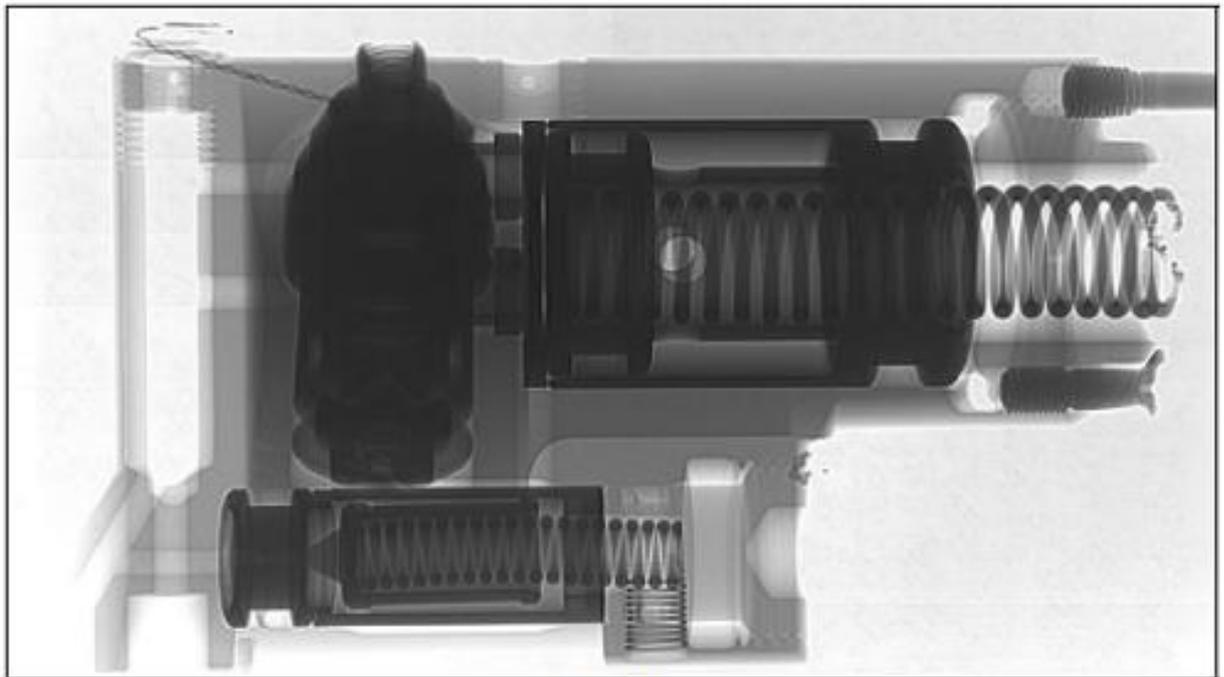


Figure 14

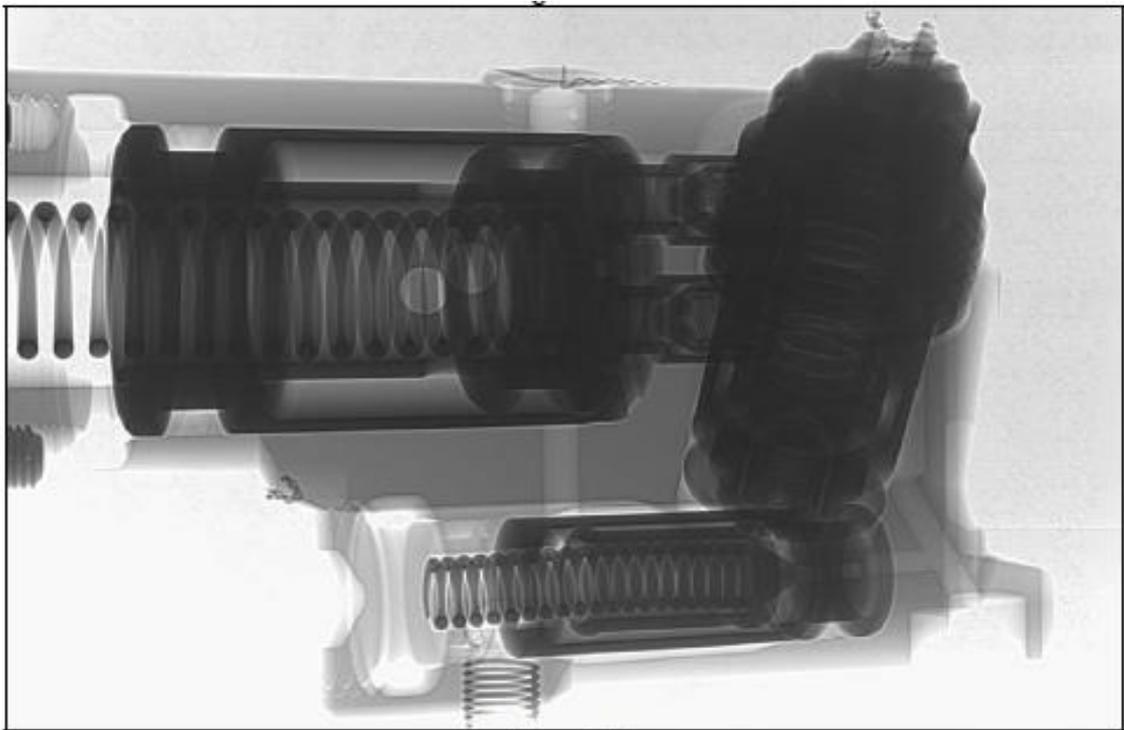


Figure 15

The compensator was then set up for hydraulic testing. Normally, the compensator and damper are tested as one unit. Due to the noted damage, two aluminium test plugs were installed at the normal interface between the compensator and damper, and the compensator was clamped to the hydraulic test bench so the compensator could be tested independently; see Figure 16. Tests were selected from reference (a) that applied to the compensator and were modified as needed to adjust for the damper not being attached.



Figure 16

Test 1 – External leakage check.

Apply 900 psi of pressure to port A while ports B, C & D are closed, hold pressure for 2 minutes. Next, reduce pressure to 30 psi, and hold pressure for 2 minutes.

Criteria – There shall be no external leakage. Results – Pass.

This test is an initial setup test to ensure there are no external hydraulic leaks.

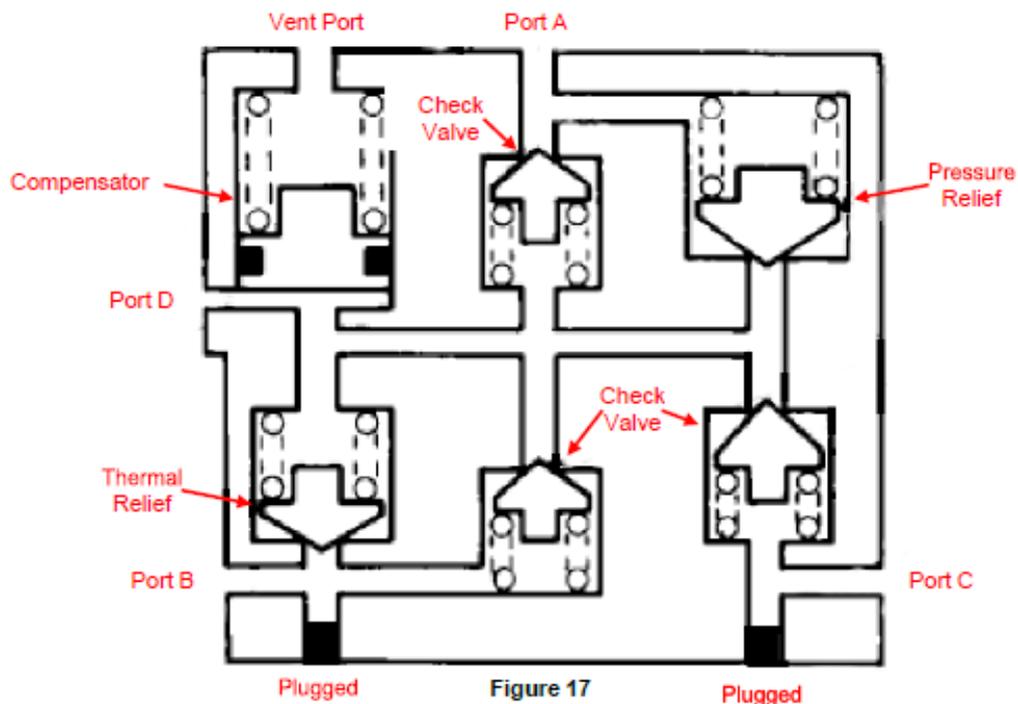
Test 2 – Thermal relief and check valve leakage test.

3000 psi was applied to ports B and C while port A was closed and port D was monitored.

Criteria – While applying 3000 psi to ports B & C, there must be no more than 10 cc per minute flow from port D.

Results – Pass.

This test is to check if check valve B, check valve C and the thermal relief valve are sealing within an acceptable range; see the hydraulic schematic circuit of the compensator in Figure 17.



Test 3a – Thermal relief valve test.

Slowly increase pressure to port B while ports A and C are closed, until an increase of flow at port D occurs.

Criteria – The increase in flow should occur between 3400 and 4600 psi.

Result – Pass. The increase in flow from port D occurred at 4400 psi.

Continue test with step 3b.

Test 3b – Thermal relief valve test continuation.

After the increase in flow occurs, lower the pressure to 3000 psi.

Criteria – After a one-minute seating period, check that the flow from port D does not exceed 10 cc per minute.

Result – Fail. There was 10 cc of leakage measured in 18 seconds.

Test 4a – Pressure relief valve test.

Apply 45 psi to port D with ports B and C closed and monitoring port A. Criteria – There shall be no flow from port A.

Result – Pass. Continue test with step 4b.

Test 4b – Pressure relief valve test continuation.

Slowly increase pressure to port D until flow starts from port A.

Criteria – The pressure at which flow starts from port A shall be 60 – 120 psi.

Result – Pass, flow initiated at 90 psi. Continue test with step 4c.

Test 4c – Pressure relief valve test continuation.

Decrease pressure to port D until flow decreases to less than 10 drops per minute.

Criteria – The reset pressure shall not be more than 35 psi less than the pressure result in Test 4b and not less than 45 psi.

Result – Pass, reset at 65 psi.

Test 5 – Check valve cracking pressure test.

With port B open and ports C and D closed, slowly apply pressure to port A until flow starts from port B.

Criteria – Flow shall begin at port B when applied pressure reaches 25 psi or less.

Result – Pass, flow at 19 psi.

Test 6a – Compensator test.

With port C closed, a 0-100 psi gauge installed in port D and a manual shutoff valve, which is closed, in port B, apply pressure of 45 – 50 psi to port A for a short period of time and then disconnect pressure source from port A.

Tap 1 to 2 cc of fluid from port B with manual shutoff valve. Criteria – Pressure at port D shall be 28 to 38 psi.

Result – Pass, tapped 1.5 cc pressure at 29 psi. Continue test with step 6b.

Test 6b – Compensator test continuation. Tap an additional 20 cc of fluid from port B.

Criteria – Pressure at port D shall be 15 to 23 psi.

Result – Pass, pressure at 16.5 psi.

It was noted during the testing of the compensator that the oil that was exiting the compensator was very dark in colour.

DISASSEMBLY OBSERVATIONS:

The compensator portion was disassembled; see Figure 18.



Figure 18

It was noted during the disassembly process that the oil trapped inside the compensator was also a dark colour, and murky in appearance, as depicted in Figure 19. This fluid was representative of the earlier statement that during testing, “the oil that was exiting the compensator was very dark in colour”.



Figure 19

It was also noted that there was fine debris wedged within some of the seals; see Figure 20. This type of debris was found throughout the thermal relief assembly.



Figure 20



Figure 21

After removing the four bolts and the cover of the damper assembly, it was noted that the outboard spiral back-up, which is one of two back-ups that are on either side of the O-ring, was damaged; see Figure 22.

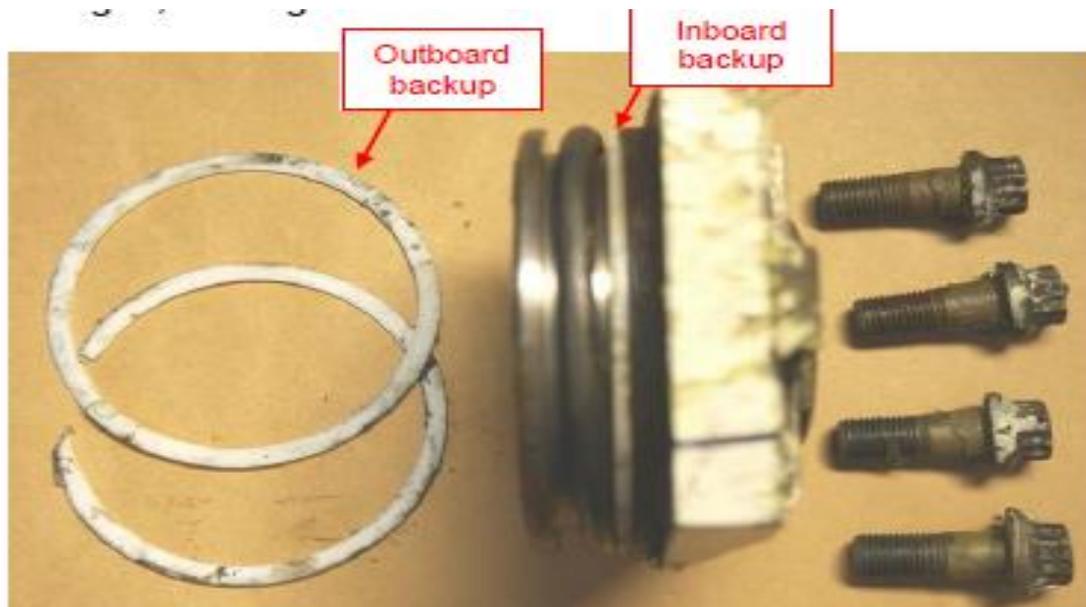


Figure 22 - Damaged backup

Portions of the damaged back-up were also found inside the damper housing after the cover was removed; see Figure 23.



Figure 23

Although portions of the damper assembly were not present to verify wear, it was noted that there were, what appeared to be, two wear areas on the portion of the damper

shaft that had fractured off; see Figure 24 and Figure 25.

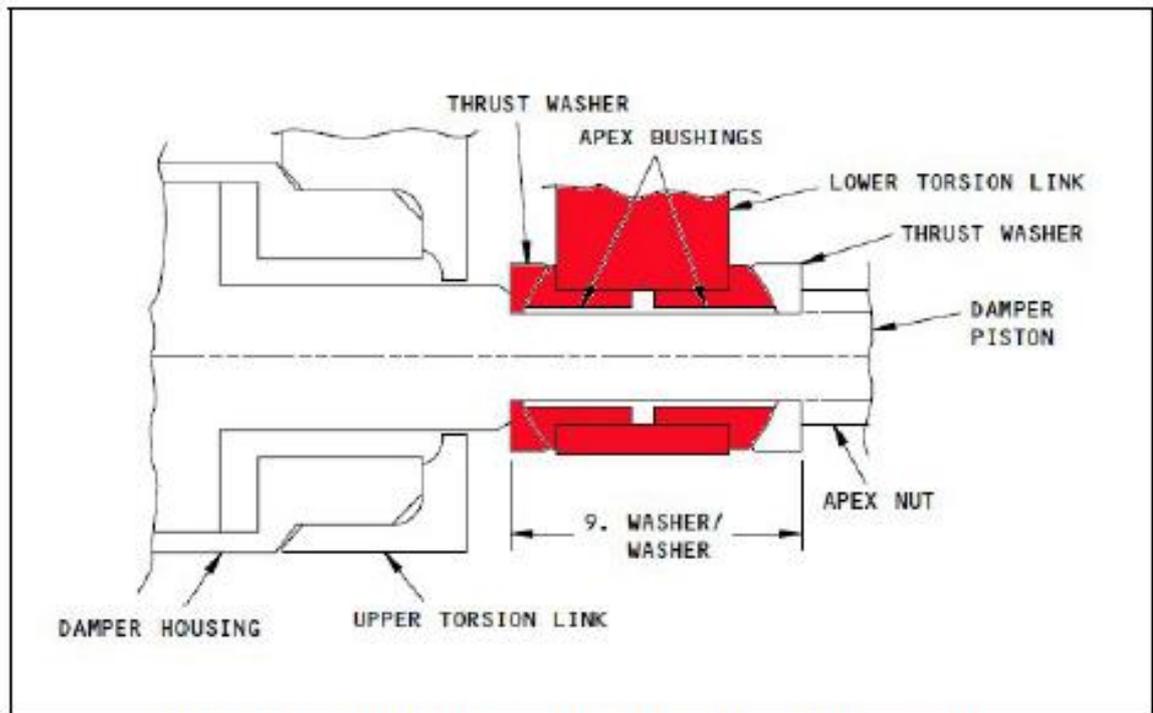
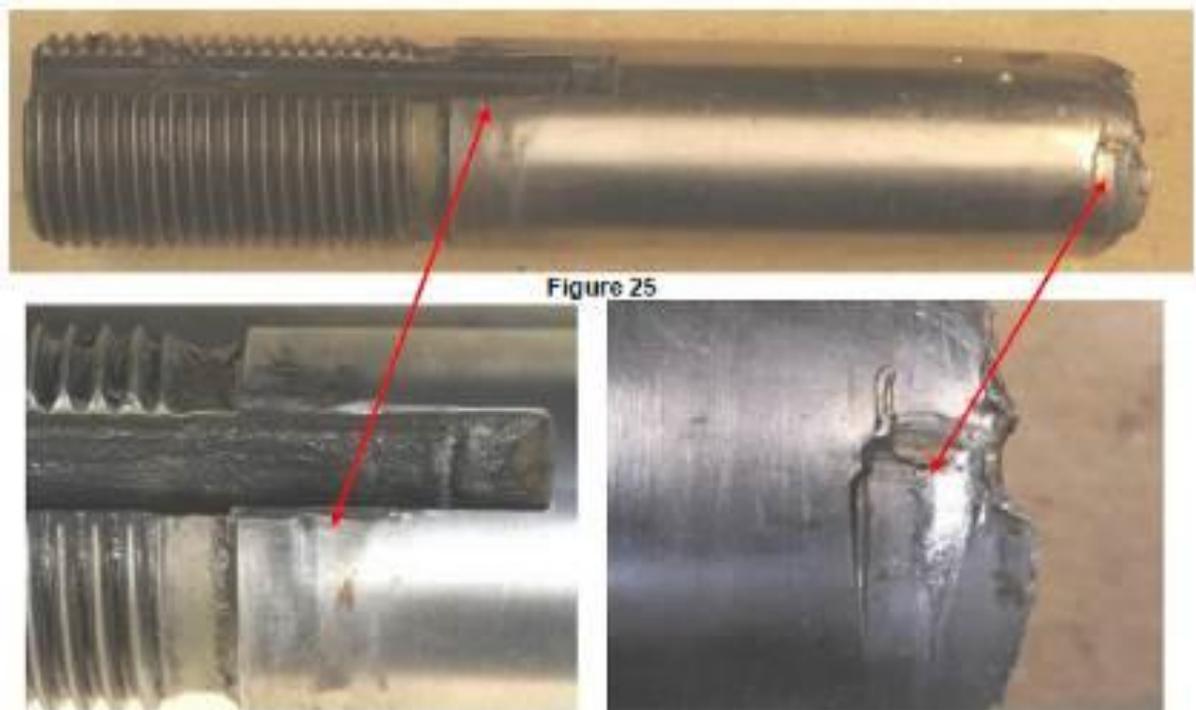


Figure 24 – Excerpt from reference (b), section 32-11-51, page 602
Parts not present are highlighted in red



Measurements identified by numbers 3 and 4 in Figure 26 were taken from the bushing end of the fractured upper torsion link; see Figure 27.

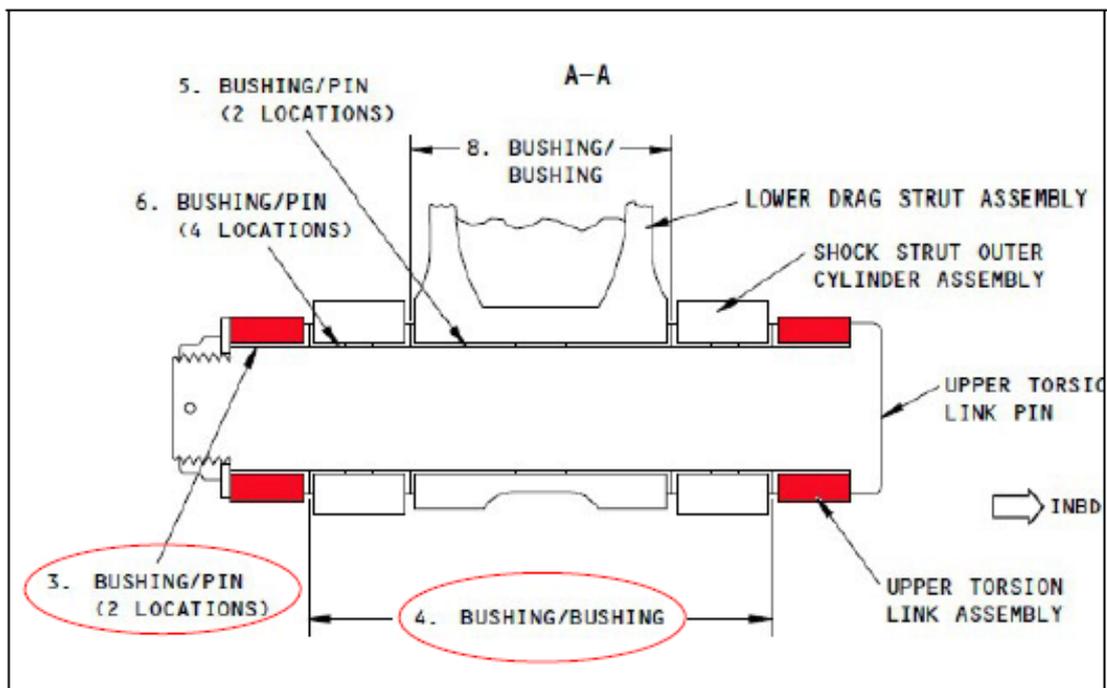


Figure 26

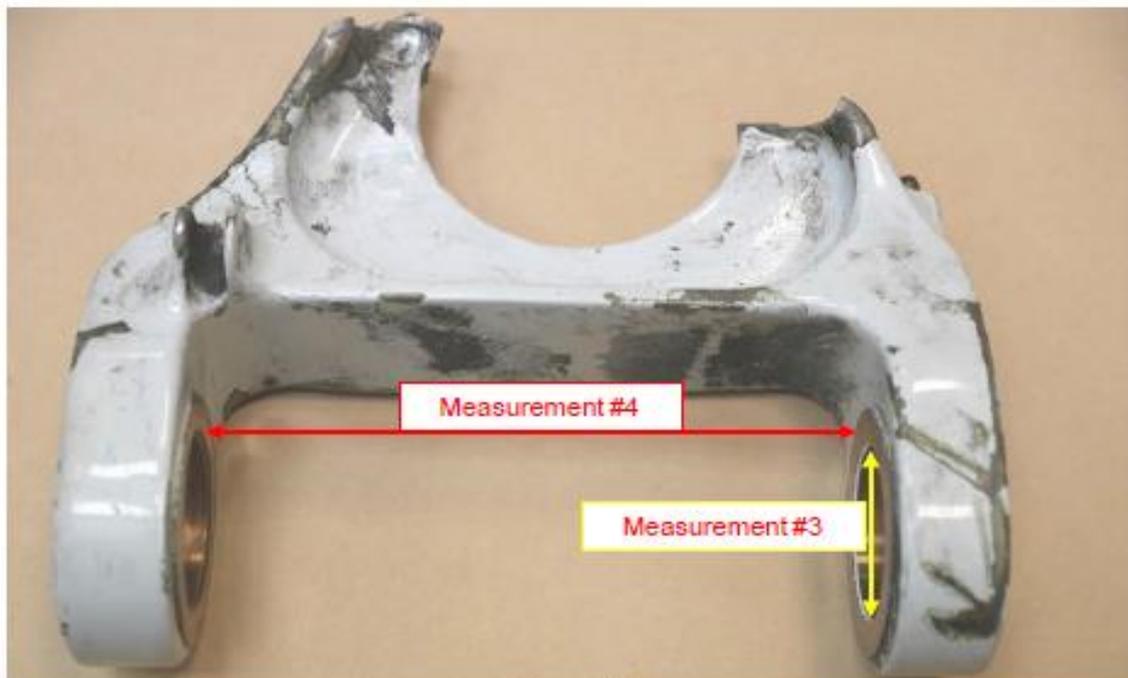


Figure 27

Per reference (b), section 32-11-51, page 603, the number 3 maximum wear dimension should be 1.7535". The left bushing inside diameter (ID) measured 1.755" and the right measured 1.756".

Per reference (b), section 32-11-51, page 603, the number 4 maximum distance between flange faces of bushings dimension should be 6.382". The distance between the flange faces of the bushings measured between 6.406" and 6.438".

While measuring the number 4 maximum distance, it was noted that there was a wear lip on one of the face flanges of one of the bushings; see Figure 28.

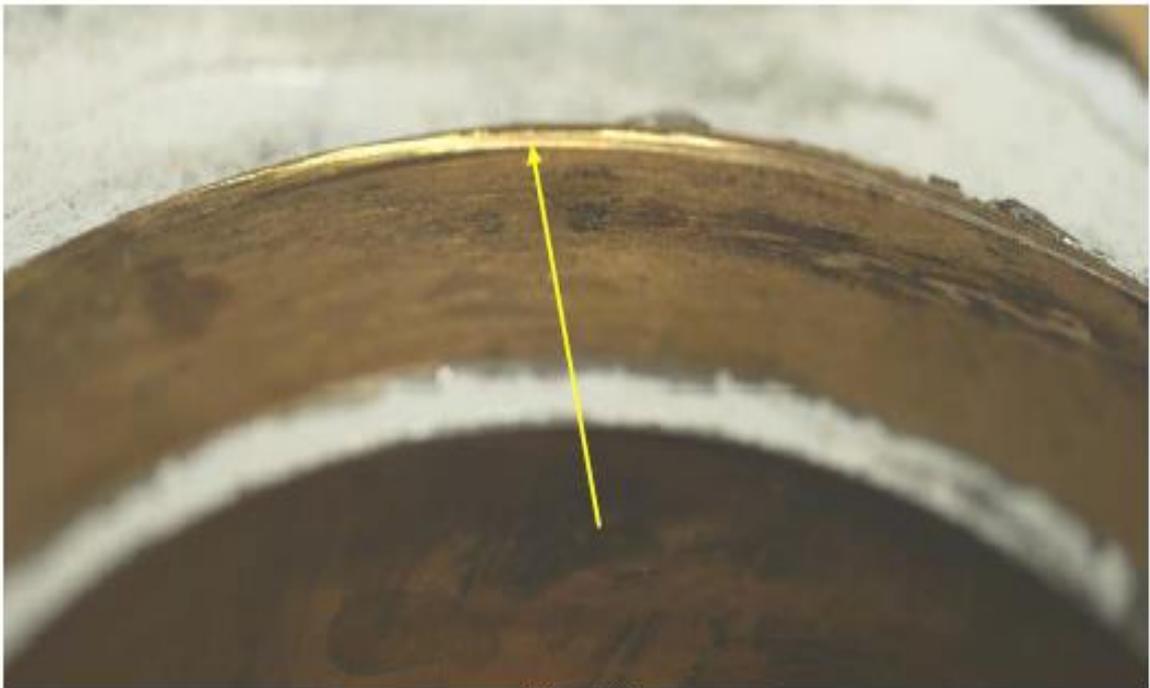


Figure 28

5.2 Annex B: FDR Analyses

Boeing Flight Data Recorder Analysis – Comair Limited 737-400 ZS-OAA Left Main Landing Gear Failure During Landing at Tambo International Airport, South Africa, on 26 October 2015

Reference: a) *Preventing Main Landing Gear Shimmy Events*, Boeing Aero Magazine 3rd quarter, dated 11-15-2013

b) *Main Landing Gear Shimmy*, Boeing Fleet Team Digest Article 737-FTD-32-11001

c) 737CL Flight Crew Training Manual, The Boeing Company, Revision Date: June 30, 2015

FDR Data Analysis

Time history plots of the pertinent longitudinal and lateral-directional parameters are attached as Figures 1 through 4. Figures 1 and 2 show the final approach and landing while Figures 3 and 4 focus on the touchdown and initial portion of the rollout. The FDR data show the airplane on a flaps 30 manual approach at approximately 1000 feet radio altitude with the speedbrake handle in the armed detent (Figure 1). Tambo International Airport is situated 5558 feet above sea level, and the pressure altitude of the airport at the time of landing was approximately 5100 feet. A combination of latitude/longitude data, Instrument Landing System (ILS) frequency (not shown), and magnetic heading data (Figure 2) indicate the airplane was positioned to land on Runway 03R. The winds were out of the south-southwest at approximately 5 knots, increasing to close to 15 knots prior to touchdown (Figure 2). This resulted in a predominant tailwind component (runway magnetic heading = 34 degrees).

The landing reference speed (VREF) for the airplane's configuration was 133 knots. Below 1000 feet radio altitude, computed airspeed was 148 knots (VREF+15), on average, and reached as high as 154 knots (VREF+21) prior to flare (Figure 1). High rate column and control wheel inputs were observed during the approach, resulting in a fluctuating pitch attitude and bank angle, respectively (Figures 1 and 2). The fluctuations in pitch attitude contributed to variations in calculated vertical speed (relative to the center of gravity [CG]) between -500 and -1500 feet/minute (Figure 1). Furthermore, the airplane was consistently above the glide path, as evidenced by glideslope deviation. The autopilot pitch mode and roll mode were engaged in Glideslope and Very High Frequency (VHF) Omnidirectional Range

(VOR)/Localizer mode, respectively (not shown), indicating Flight Director (FD) guidance (FD switches were on [not shown]), relative to glideslope and localizer deviation, was available to the crew. Flare was initiated with a nose-up column input at approximately time 4767 seconds at a radio altitude of around 65 feet (Figure 3). The throttles reached forward idle (0 degrees throttle lever angle [TLA]) by time 4771 seconds. The calculated vertical speed became positive momentarily around time 4772 seconds, as the airplane floated prior to touchdown. The airplane was experiencing an approximate 10-knot tailwind below 100 feet radio altitude (Figure 4). Touchdown occurred at time 4776 seconds at a computed airspeed of 139 knots (VREF+6) and a ground speed of 167 knots (Figure 3). The airplane had an approximate 2-3 degree left bank angle and a 1-degree right drift angle (ground track right of heading) at touchdown (Figure 4). The calculated sink rate (negative vertical speed) at touchdown was around 1.8 feet/second with a normal load factor of approximately 1.1 g's (Figure 3).

Closure rate was also calculated and is shown in Figure 3 during flare and touchdown. The closure rate at touchdown was approximately 3 feet/second. Closure rate is the rate of change of distance between the landing gear and the local terrain and is generated by calculating the sink rate of the main landing gear and accounting for any runway slope near the point of touchdown (based on Jeppesen runway information). The effect of an upsloping (positive) runway would increase the closure rate of the main landing gear with the runway compared to the airplane sink rate at the CG. Conversely, the effect of a downsloping (negative) runway would decrease the closure rate of the main landing gear with the runway compared to the airplane sink rate at the CG. In addition, the effect of a roll rate at touchdown would increase the main landing gear closure rate on the down-wing side. The runway slope for Runway 03R is 0.52%.

Following touchdown, the speedbrakes automatically deployed and wheel braking was applied, although it was unclear whether it was due to manual or autobrake application (Figure 3). Thrust reversers were commanded approximately 4 seconds after touchdown. Around this same time, as de-rotation completed, the left main gear collapsed, as evidenced by a rapid increase in bank angle to the left and a momentary increase in pitch attitude (Figures 3 and 4). Spikes were observed in both longitudinal acceleration and normal load factor, and lateral acceleration shifted significantly to the right. The left wing trailing edge flap measurement also indicated a lower flap setting than the right after time 4782 seconds (Figure 3). As the landing rollout continued, the crew commanded right control wheel and right rudder (note: significant bias exists in rudder deflection data) [Figure 4]. The thrust reversers remained deployed throughout the rollout, but the left engine began spooling down after time 4795 seconds (Figure 3). The airplane came to a stop approximately 40 seconds after touchdown, left of the runway centreline.

Shimmy Event Discussion

At the time of writing, there has been no confirmation that the main landing gear collapsed due to a shimmy oscillation. However, the characteristics of the landing are consistent with past landing gear shimmy events. The airplane touched down at a high ground speed and low sink/closure rate. The air/ground discrete transition to GROUND occurred approximately one second after touchdown, indicating that the struts were extended for that period of time. As a result, the torsion links of the shimmy damper remained in an extended, vertical position, where the damper has less mechanical advantage for longer periods of time. Despite the presence of shimmy damper hardware, which is designed to reduce the torsional vibration energy generated during landing, airplanes occasionally experience main landing gear shimmy.

The reference (a) Boeing Aero Magazine article and reference (b) Fleet Team Digest article provide information on the causes of shimmy and how Boeing has addressed the issue. Due to the geometry of the torsion links, the shimmy damper is most effective when the landing gear strut is compressed in the ground mode. Lower touchdown descent rates increase the likelihood of a shimmy damper failure. It is important to note, however, that proper maintenance of the gear components is the best way to prevent

shimmy damper failures. The possibility of landing gear shimmy events is greater at high altitude airports. The Aero Magazine article concludes with the following:

Boeing also recommends that pilots strive for a landing with normal sink rates with particular emphasis on ensuring that the auto speedbrakes are armed and deploy promptly at touchdown. An overly soft landing, or a landing in which the speedbrakes do not promptly deploy, allows the landing gears to remain in the air mode longer, which makes them more vulnerable to shimmy. This is especially true when landing at airports located at higher elevations, where the touchdown speed is increased.

Operational Guidance

Stabilized Approach Assessment

The following statements were extracted from the reference (c) 737 CL Flight Crew Training Manual with regards to the Flight Safety Foundation's published criteria for flying a stabilized approach. It recommends that a go-around should be initiated if the approach becomes unstabilized under 1000 feet above the ground for instrument meteorological conditions and under 500 feet for visual meteorological conditions.

Stabilized Approach Recommendations

Maintaining a stable speed, descent rate, and vertical/lateral flight path in landing configuration is commonly referred to as the stabilized approach concept.

Any significant deviation from planned flight path, airspeed, or descent rate should be announced. The decision to execute a go-around is not an indication of poor performance.

Note: *Do not attempt to land from an unstable approach.*

Recommended Elements of a Stabilized Approach

The following recommendations are consistent with criteria developed by the Flight Safety Foundation. All approaches should be stabilized by 1,000 feet AFE in instrument meteorological conditions (IMC) and by 500 feet AFE in visual meteorological conditions (VMC). An approach is considered stabilized when all of the following criteria are met:

- *the airplane is on the correct flight path*
- *only small changes in heading and pitch are required to maintain the correct flight path*
- *the airplane should be at approach speed. Deviations of +10 knots to – 5 knots are acceptable if the airspeed is trending toward approach speed*
- *the airplane is in the correct landing configuration*
- *sink rate is no greater than 1,000 fpm; if an approach requires a sink rate greater than 1,000 fpm, a special briefing should be conducted*
- *thrust setting is appropriate for the airplane configuration*
- *all briefings and checklists have been conducted.*

Specific types of approaches are stabilized if they also fulfill the following:

- *ILS and GLS approaches should be flown within one dot of the glide slope and localizer, or within the expanded localizer scale*
- *approaches using IAN should be flown within one dot of the glide path and FAC*
- *during a circling approach, wings should be level on final when the airplane reaches 300 feet AFE.*

Unique approach procedures or abnormal conditions requiring a deviation from the above elements of a stabilized approach require a special briefing.

Note: *An approach that becomes unstabilized below 1,000 feet AFE in IMC or below 500 feet AFE in VMC requires an immediate go-around.*

These conditions should be maintained throughout the rest of the approach for it to be considered a stabilized approach. If the above criteria cannot be established and maintained until approaching the flare, initiate a go-around.

At 100 feet HAT for all visual approaches, the airplane should be positioned so the flight deck is within, and tracking to remain within, the lateral confines of the runway edges extended.

As the airplane crosses the runway threshold it should be:

- *stabilized on approach airspeed to within + 10 knots until arresting descent rate at flare*
- *on a stabilized flight path using normal maneuvering*
- *positioned to make a normal landing in the touchdown zone (the first 3,000 feet or first third of the runway, whichever is less).*

Initiate a go-around if the above criteria cannot be maintained.

Maneuvering (including runway changes and circling)

When maneuvering below 500 feet, be cautious of the following:

- *descent rate change to acquire glide path*
- *lateral displacement from the runway centerline*
- *tailwind or crosswind components*
- *runway length available.*

Below 1000 feet radio altitude, the airplane did not adhere to three of the above recommended stabilized approach criteria. These criteria are summarized below:

• *the airplane is on the correct flight path.* The recorded glideslope deviation indicate the airplane was above the intended glide path.

• *the airplane should be at approach speed.* For a tailwind approach, the recommended approach speed (VAPP) is VREF+5, which in this case was 138 knots. On average, computed airspeed was 148 knots (VAPP+10) but reached as high as 154 knots (VAPP+16) prior to flare, which exceeded the allowable deviation above approach speed by 6 knots (10 knots is allowed).

• *sink rate is no greater than 1000 fpm.* Throughout the approach, there were several sink rate exceedances of 1000 fpm.

Flare Guidance

The Flight Crew Training Manual also contains the following recommendations that are applicable to this event:

Initiate the flare when the main gear is approximately 20 feet above the runway by increasing pitch attitude approximately 2° - 3°. This slows the rate of descent.

After the flare is initiated, smoothly retard the thrust levers to idle, and make small pitch attitude adjustments to maintain the desired descent rate to the runway. A smooth thrust reduction to idle also assists in controlling the natural nose-down pitch change associated with thrust reduction. Hold sufficient back pressure on the control column to keep the pitch attitude constant. Ideally, main gear touchdown should occur simultaneously with thrust levers reaching idle.

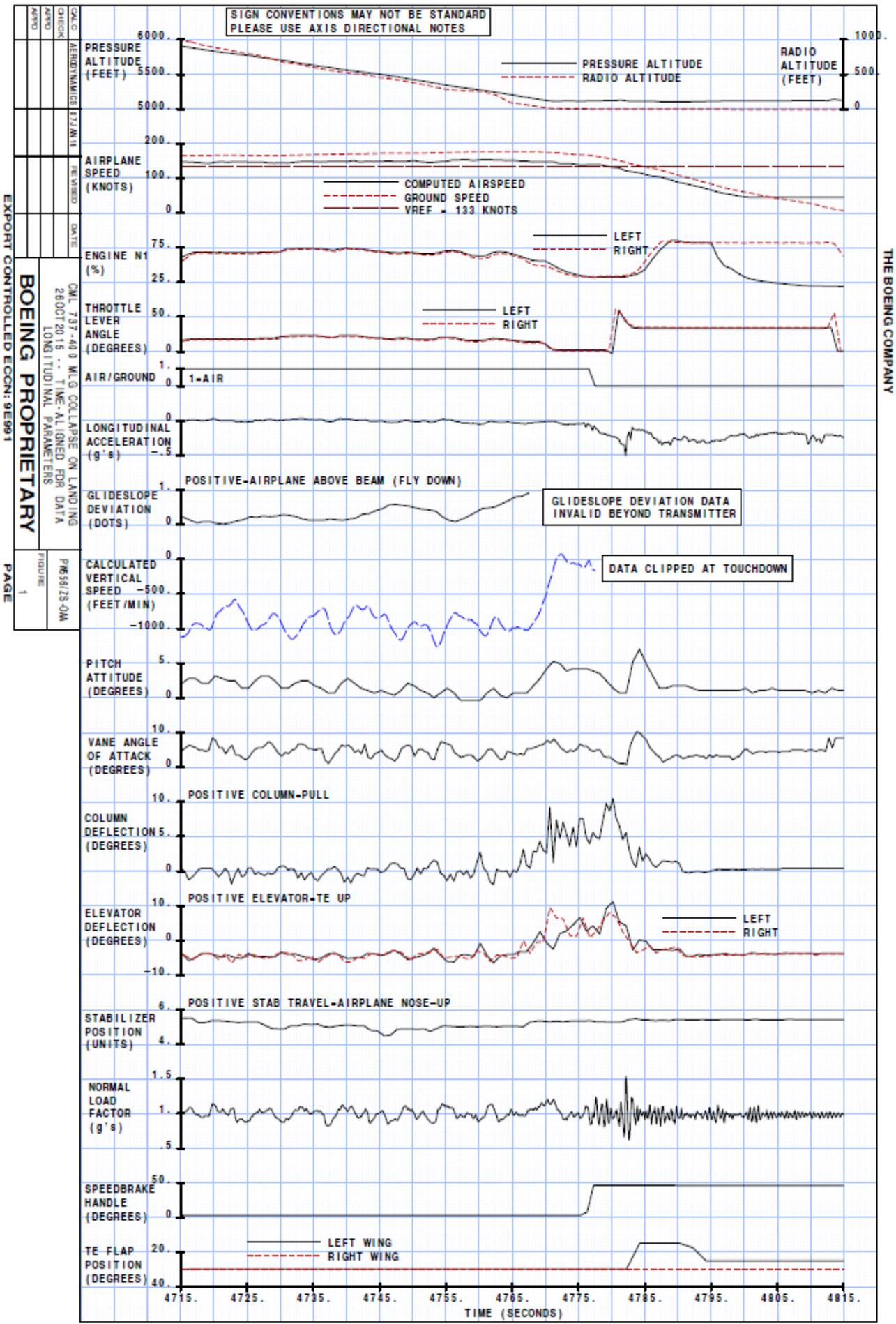
Do not allow the airplane to float or attempt to hold it off. Fly the airplane onto the runway at the desired touchdown point and at the desired airspeed.

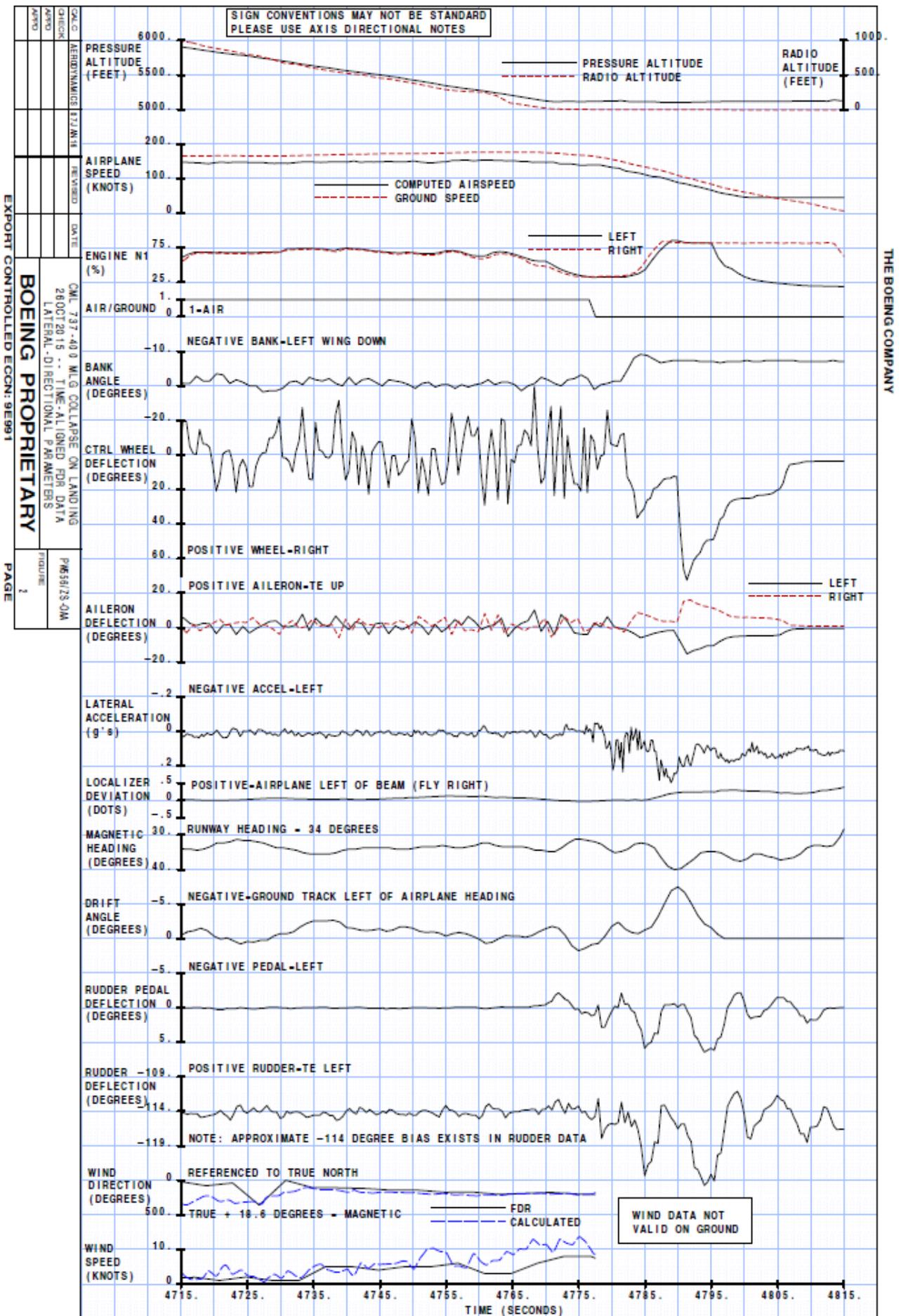
Prolonged flare increases airplane pitch attitude 2° to 3°. When prolonged flare is coupled with a misjudged height above the runway, a tail strike is possible. Do not prolong the flare in an attempt to achieve a perfectly smooth touchdown. A smooth touchdown is not the criterion for a safe landing.

During final approach, flare was initiated early at a radio altitude of approximately 65 feet, which is higher than the recommended 20 feet. The early flare initiation contributed to the airplane float that led to touchdown at a low sink rate.

Conclusion

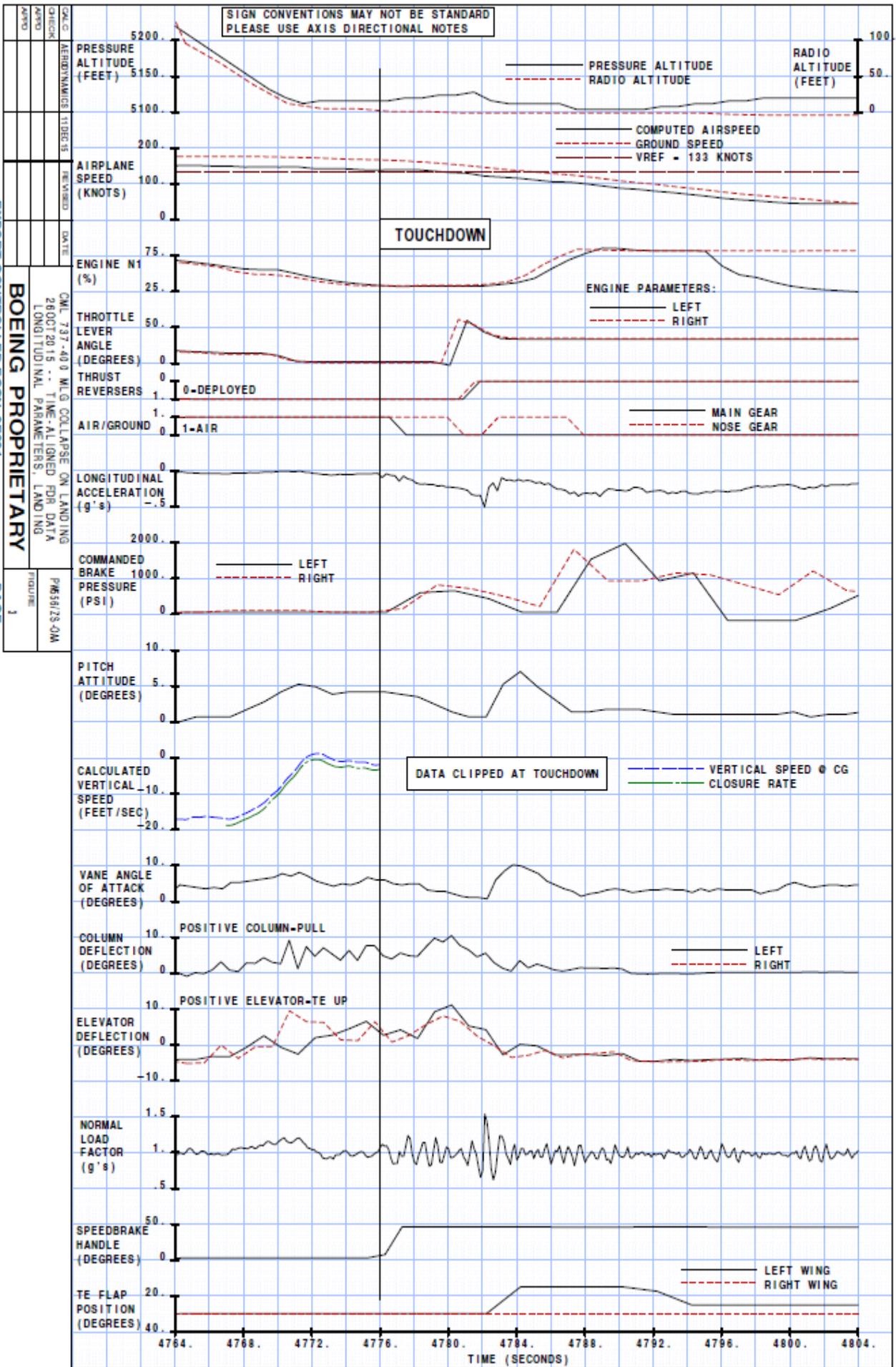
A manual approach was performed by the crew that was determined to be unstable, based on the stabilized approach criteria. A combination of a tailwind and high approach speed, while landing at a high altitude airport, resulted in excessive ground speed (167 knots) at touchdown. An extended flare that was the result of an early flare initiation led to touchdown at a low sink rate (1.8 feet/second). The left main gear collapsed approximately 5 seconds after touchdown, and the airplane came to a stop around 35 seconds later. Although the official investigation has not determined the cause of the landing gear collapse, prior service experience on the 737 has shown that touchdown at high ground speeds and low sink rates increases the likelihood of the initiation of main gear shimmy. Prior service history on the 737 has shown that gear collapse is a possible outcome of shimmy.

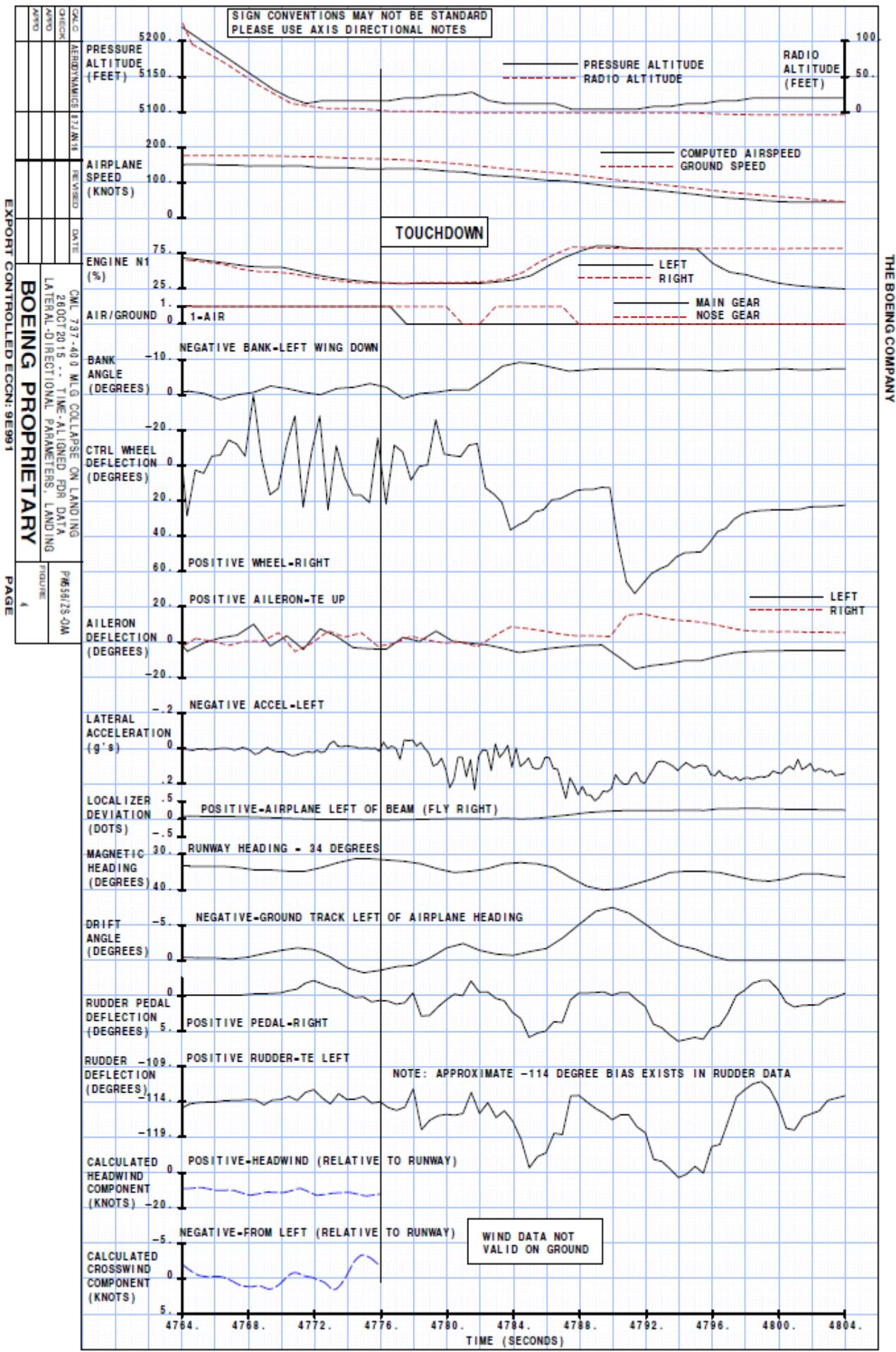




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COMAIR LIMITED COMMENTS ON 'AIRCRAFT AND ACCIDENT REPORT AND EXECUTIVE SUMMARY' Reference CA18/2/3/9494

Our discussion dated 10 February 2017 refers.

Comair Limited's comments as requested by the SACAA:

Comair Operations and Safety Management do not agree with some aspects of the preliminary report and probable cause, as listed in abovementioned document. More technical information on which Comair's assessment is based, is available if required.

1. Cause of the Gear Failure. As indicated by the numerous similar failures that have occurred on Boeing 737-400 aircraft throughout the world, and at least three since Comair's accident, there is clearly a design fault with the gear in combination with this aircraft:
 - *The conditions at actual touchdown and whether the gear can handle these conditions, are what is important and not what precedes this event or what follows after. Boeing agrees that a high-speed soft landing can cause the excessive shimmy with resultant failure. However, nowhere does Boeing state what the actual limitations are in terms of the limiting groundspeed and or touch-down g forces. This aircraft did a flap 30 landing, while Boeing allows flap 15 landings and even flapless landings, which will result in much higher landing speeds than were recorded here, but nowhere (QRH included) does Boeing state that pilots need to beware of shimmy conditions at high speed and with soft landings and that this can cause a failure of the gear. Boeing magazine AERO QTR 3, 13 is not an official, regulated document that requires specific action, it is merely advisory. Comair pilots were never advised that these conditions may constitute a gear failure.*
 - *Similarly, Boeing Fleet Team Digest 737-FTD-32-11001 dated 24 Sep 2014, which discusses this problem in detail, gives no indication of what exactly is expected of pilots and only addresses maintenance issues, two of which were found present in this case:*
 - a. *In the SACAA report findings, paragraph 3.1.6 it states that the shimmy damper failed the lab-test and that fluid was found in the thermal relief valve, which could have contributed to the shimmy damper failure.*
 - b. *Also, in the same document paragraph 3.1.7 it states that significant wear was on the upper torsion link bushing and flange, which could contribute to undamped vibration continuation.*

2. Stable Approach. Throughout this report it is contended that the approach was unstable due to an excessive tailwind and rate of descent and that the pilots should not have landed off this approach. Comair disagrees with this assumption that the approach was unstable:
 - *Approach Groundspeed. The threshold wind given to the pilots by ATC was 034 degrees at 10 knots, which is the speed that pilots use as reference for landing and in this case constitutes a 10 knot headwind. The actual wind (FOQA read-outs) at 1000 feet was 160 degrees at 12 knots, at 500 feet 106 degrees at 2 knots, at 200 feet 175 degrees at 12 knots and at 26 feet 190 at 12 knots. From 200 feet the pilots' eyes are on the runway for landing and there is no way of monitoring the actual tailwind component, which in this case was marginally above the 10 knot tailwind limit only at round-out. It is also evident that the wind was not constant and therefore the pilots would not have had any indication that they were exceeding the tailwind limitation.*
 - *Rate of Descent (ROD). The report states that the ROD exceeds the stable approach allowable rate of minus 1000 feet/min on several occasions during the approach. The records used to indicate this seem to reflect the VSI which is not an accurate indication of actual sustained descend rate. On the FOQA graphs, the actual height vs the glide-path, never deviates more than ½ a dot, where up to 1 dot deflection is allowed for a stable approach. During high speed approaches, as is the case in JNB's hot and high conditions, to maintain a 3 degree slope, your ROD to maintain the slope can be as high as 800 feet/min under zero wind conditions at 145 knot Vref. This only allows 200 feet/min deviation before the VSI indicates higher than 1000 feet/min descent and any pilot knows that even under*

slightly bumpy conditions as were experienced here, the VSI will exceed 1000 feet/min instantaneously on several occasions, even on autopilot. It is not the immediate indication that is important, but whether the glideslope can be maintained within acceptable limits that constitute a stable approach.

3. *Landing.* *The report also states that the landing was too soft after a too-early start of the round-out. At hot and high airports such as JNB it is important to start reducing your ROD a bit earlier than normal, as many 'foreign' pilots have learnt to the disgust of their passengers. This reduction in ROD is not the actual round-out, which took place at the prescribed height of 20 feet. The touchdown was at 1,1g which was not overly soft as indicated by the speed-brake deploying immediately and took place within the landing-mat as recommended.*
4. *Maintenance.* *Comair, through SAAT performed all the required Boeing maintenance schedules pertaining to the landing gear on this aircraft type and the problems identified could not have been picked up during normal maintenance as specified.*

Conclusion. *It is therefore Comair's contention that no blame for this accident can be afforded to the pilots, as the approach was stable within the Comair SOPs, as ratified by the SACAA and the landing was carried out well within the specifications as officially published by Boeing. Maintenance can also not be blamed as all required inspections were duly carried out.*

Comair Implemented Recommendations. *Immediately after the accident, Comair voluntarily implemented the following recommendations in order to prevent a similar gear failure in the future:*

1. *A Pilot's notice was issued informing pilots of the potential gear shimmy and failure problem during high-speed and soft landings. No specifics were given as none were forthcoming from Boeing.*
2. *Comair Engineering, through SAAT immediately inspected the whole Comair B737-400 fleet in order to establish further potential excessive wear and more regular inspections have been scheduled (over-and-above Boeing requirements) in order to monitor the fleet going forward.*