Piper PA-28R-200-2 Cherokee Arrow II, G-BKCB

Contents

Air Accident Investigation - Summary table

AAIB Bulletin No: 11/2003	**Ref: EW/C2000/12/2**	**Category: 1.3**
Aircraft Type and Registration:	Piper PA-28R-200-2 Cherokee Arrow II, G-BKCB	
No & Type of Engines:	1 Lycoming IO-360-CIC piston engine	
Year of Manufacture:	1974	
Date & Time (UTC):	3 December 2000 at 1503 hrs	
Location:	Warren Farm, Lambourne, Berkshire	
Type of Flight:	Private	
Persons on Board:	Crew - 1	Passengers - 3
Injuries:	Crew - 1 (Fatal)	Passengers - 3 (Fatal)
Nature of Damage:	Aircraft destroyed	
Commander's Licence:	Private Pilot's Licence with IMC rating	
Commander's Age:	29 years	
Commander's Flying Experience:	224 hours (of which 203 were on type)	
	Last 90 days - 7 hours	
	Last 28 days - 1 hour	
Information Source:	AAIB Field Investigation	

Synopsis

Whilst apparently flying normally in clear air at a height of around 4,200 feet, at or below manoeuvre speed, the aircraft suffered an in-flight structural failure within five seconds of deviating from straight and level flight. The main part of the aircraft was severely disrupted by trees just before ground impact, but there was no fire. Detailed examination and analysis of the wreckage revealed that the first event in the break-up sequence had been the failure, in download, of the outer section of the left wing. No pre-existing defects were identified in the structure of the wing or the flying control systems, and there was no evidence of atmospheric turbulence or any factor requiring the pilot to carry out an evasive manoeuvre. The investigation concluded that a manoeuvre, resulting from unintentional and unusual control inputs by either the pilot and/or the front seat passenger, sufficient to overload the wing structure, was the most likely cause of the wing failure.

History of flight

The pilot had been authorised by a Flying Club for a one hour flight in the local area of Thruxton Airfield, with three passengers. The aircraft was refuelled with 55 litres of AVGAS prior to the flight and the refueller recalled that the fuel level was about two inches above the 'tabs'; a total load of about 153 litres (34 imp gall). The weight of those on board was estimated but the take-off weight was likely to have been just below the maximum allowed of 2,650 lb. At the time of the accident this would have reduced to around 2,600 lb. The centre of gravity was determined to have been within limits.

Radio transmissions are not recorded at Thruxton. However, the Airfield Operations Manager stated that the aircraft departed from Runway 25 at about 1430 hrs, with four people on board and that the pilot reported he was leaving the zone and would call again if he changed frequency, or when he rejoined the circuit. No subsequent transmissions were heard from G-BKCB on the Thruxton, or any other frequency.

Data from the Watchman and 23 cm radar heads at London Heathrow Airport were analysed and a series of contacts was identified which were considered to be G-BKCB. The first contact, at 1433 hrs, was a primary radar return about 5 nm north of Thruxton. The aircraft had tracked northerly towards the White Horse landmark, where it manoeuvred for about a minute. There was no secondary radar information available at this time but a witness assessed that it was between 4,000 and 5,000 feet agl. The aircraft then turned east towards Sparsholt from where it turned again to track south-east for about two minutes, before turning back onto north and tracking back towards Sparsholt. It passed over Sparsholt again at 1448 hrs and continued north for about two minutes before turning right onto a south-easterly track. The first secondary radar contact was at 1452 hrs when the aircraft was tracking towards the town of Grove at 4,200 feet amsl. It continued on this south-east track until it crossed the A34(T) road, when it turned right to track towards the west and, at 1454 hrs, re-crossed the A34(T) at East Ilsley. The aircraft was at 4,200 feet amsl and the average ground speed when on this south-east track was of the order of 126 kt.

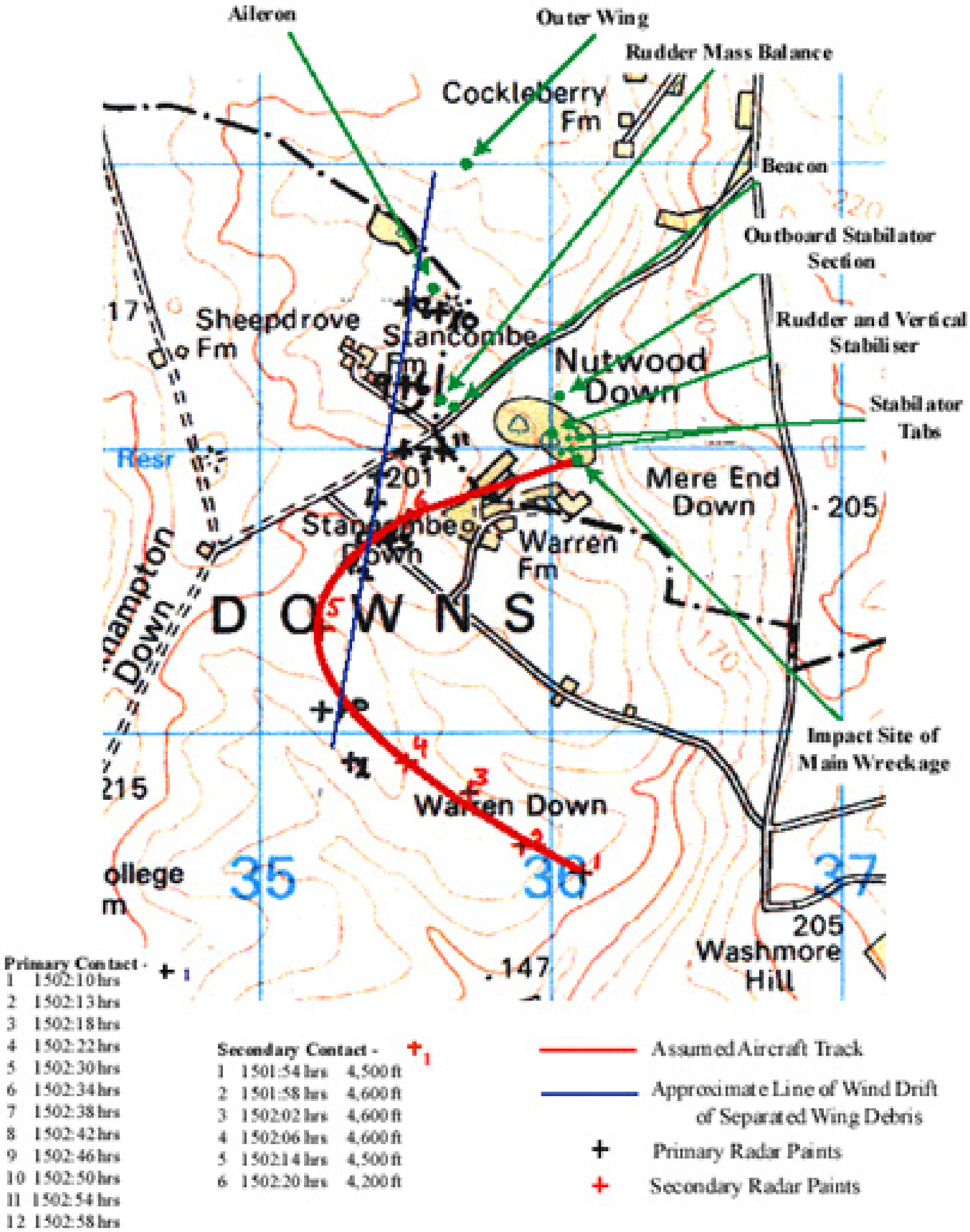
The reports from witnesses on the final stage of the flight were generally consistent. The aircraft deviated from a normal flight path and was seen to be rolling and pitching while descending. This was also described as "spinning" or "doing aerobatics" and the engine/propeller noise was heard to increase and then stop. Pieces of structure were seen to fall from the aircraft and about a third of the left wing was seen to be missing. One observer, who was very close to the accident site, reported that the aircraft passed in front of him from his left. He recollected that about two thirds of the left wing was "snapped off", the right wing was tilted towards him and the wing appeared to be on top of the aircraft. As it passed over the wood, the fin "flew off' followed by "both tailplanes" as the rear fuselage disintegrated into a number of smaller pieces, some of which drifted down wind as they fell. The remainder of the aircraft then passed through tree tops and into a small copse.

Figure 1 shows the radar plot of the final stage of the flight from 1501:54 hrs. Point Nos 1 to 4 are at four second intervals and indicate that the aircraft was in stable flight, at an altitude of about 4,500 feet, with a ground speed of approximately 117 kt. There were two more secondary returns, the first at 1502:14 hrs and the second, and final, one at 1502:20 hrs, which showed an altitude of 4,200 feet. The majority of the primary contacts shown were considered likely to be from parts of the aircraft which had separated in flight, possibly from the region just after the secondary radar point No 4. No secondary return was recorded for time 1502:10, although the recording interval of the system is such that a secondary radar return would only be expected for that time had the aircraft remained in steady level flight.

Figure 1

Figure 1

Radar Plot and Ground Debris Distribution



Meteorology

An aftercast for the weather in the region of the accident was obtained from the Meteorological Office at Bracknell. The synoptic situation at 1200 hrs showed a ridge of high pressure over the Netherlands moving eastwards ahead of a low pressure area to the west of Ireland. A moderate to fresh south-south-westerly airstream covered the area.

The weather in the area was:

Surface wind	170°/12 kt
2,000 feet	200°/28 kt
4,000 feet	210°/35 kt
Visibility	30 km
Weather	Nil
Cloud	2 okta cumulus base 2,500 feet, 1 okta stratocumulus base 5,000 feet
Temp/Dewpoint	+10°C/+6°C
QNH	1012 mb

Witnesses reported small amounts of cloud in the area, and a "brisk" wind. The aircraft was not reported by anyone to have been other than in clear air.

Aircraft Information

The aircraft was a Piper PA-28R-200-2 Cherokee Arrow II, and was equipped with a 200 HP engine, driving a constant speed two bladed propeller, and a retractable tri-cycle landing gear. It had been constructed in 1974, since when it had flown for a total time of some 4,000 hours. The aircraft's most recent maintenance activity had been an annual check, some 30 hours prior to the accident.

Pilot's flying experience

The pilot underwent flying training in the USA and an American PPL was issued to him on 20 April 2000. A UK PPL was issued on 22 September 2000 and included Single Engine Piston (Land) and Multi Engine Piston (Land) ratings. He flew a 'check' flight in the accident aircraft on 17 November and the Flying Instructor reported that he had achieved a good standard.

Aircraft occupants

The pilot had been employed at London Heathrow Airport as an aircraft maintenance engineer with a major international airline. At his last medical, the pilot's weight was recorded as 208 lbs. The other occupants of the aircraft were a work colleague of the pilot (also an aircraft maintenance engineer) and his seven year old daughter, together with the adoptive brother of this colleague.

No witnesses were found who saw the occupants clearly as they entered and took their places in the aircraft. The position of each occupant in the aircraft was therefore not known. The degree of impact disruption of the aircraft and final distribution of the occupants did not permit the seating positions of the adults to be determined. The young child, however, was found in the remains of the rear of the aircraft cabin.

Pathology

The pathological examination of the aircraft occupants revealed that all had died from multiple injuries. No evidence was found of any disease in the pilot or of alcohol, drugs or any toxic substance which could have caused or contributed to the cause of the accident.

On-site wreckage distribution and examination

The majority of the severely disrupted wreckage was found concentrated in the region of the impact point, in the woods adjacent to Warren/Sheep-Drove Farm. Other items were, however, found sufficiently distant from that point to indicate that a considerable in-flight structural failure of the aircraft had occurred. The final impact took place at considerable speed and the aircraft appeared to have been steeply banked, whilst falling almost vertically through trees, before impacting the ground.

The outboard section of the left wing was recovered approximately one kilometre from the main impact site. The left aileron was also recovered from a point a considerable distance from the impact site in the general direction of this outboard wing section. When these locations were plotted on a map, together with the primary and secondary radar returns, Figure 1, the positions of both the outboard wing and the aileron were found to be close to the extended line, in a downwind direction, of the primary returns considered to have come from falling structural debris.

The wing failure had occurred between the two hinges of the left aileron, Figure 2, such that its separation led to the release of the aileron.

Figure 2

Details of separated left outer wing structure

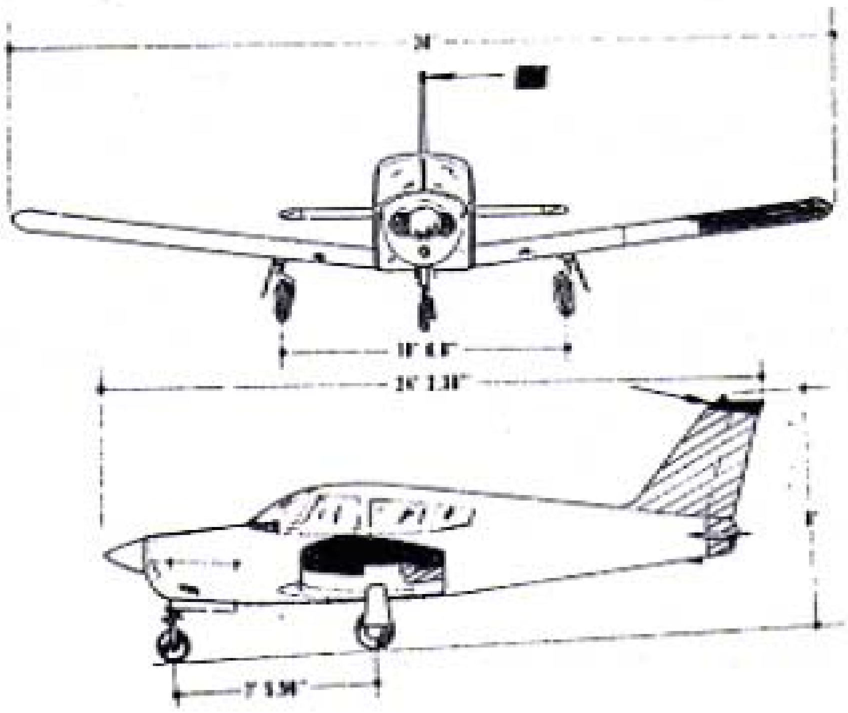
Although the stabilator outboard sections, the outer sections of the trim/anti-balance tabs, the fin and rudder were all found away from the impact point of the main wreckage, they were all close enough to indicate that they had separated during the latter stages of the descent. The positions of the remains of the inboard sections of the stabilator structure, the whole of the right wing and the left inner wing indicated that they had been attached to the fuselage at the time of impact with the ground.

Examination of the separated left outer wing section confirmed that the failure had occurred very close to the wing splice, i.e., where the extruded aluminium alloy section inboard spar is riveted to the pressed sheet aluminium alloy outer spar. The plot of the wreckage distribution indicated that the first event of the structural failure was the separation of the outermost section of the left wing. This was apparently followed by loss of a section of wing skin inboard of the initial failure, extending from the upper to the lower flange of the wing spar around the leading edge. The fin mounted rotating beacon and the rudder mass-balance weight were recovered from an area remote from other wreckage. It was calculated that the separation of these items had occurred whilst the aircraft was travelling at approximately 90° to the aircraft's initial flight path, and at an altitude not greatly below 4,200 feet. Witness marks indicated that this had occurred as a result of being struck by the section of the failed wing skin.

Detailed wreckage examination

The wreckage of G-BKCB was recovered to the AAIB for detailed examination. This revealed that all items which had separated in flight, Figure 3, with the exception of the left outer wing, the adjacent wing skin panel, the port aileron, the beacon and the rudder mass-balance, did so in a manner consistent with excessive speed reached once the aircraft was descending out of control, following the wing failure.

Figure 3



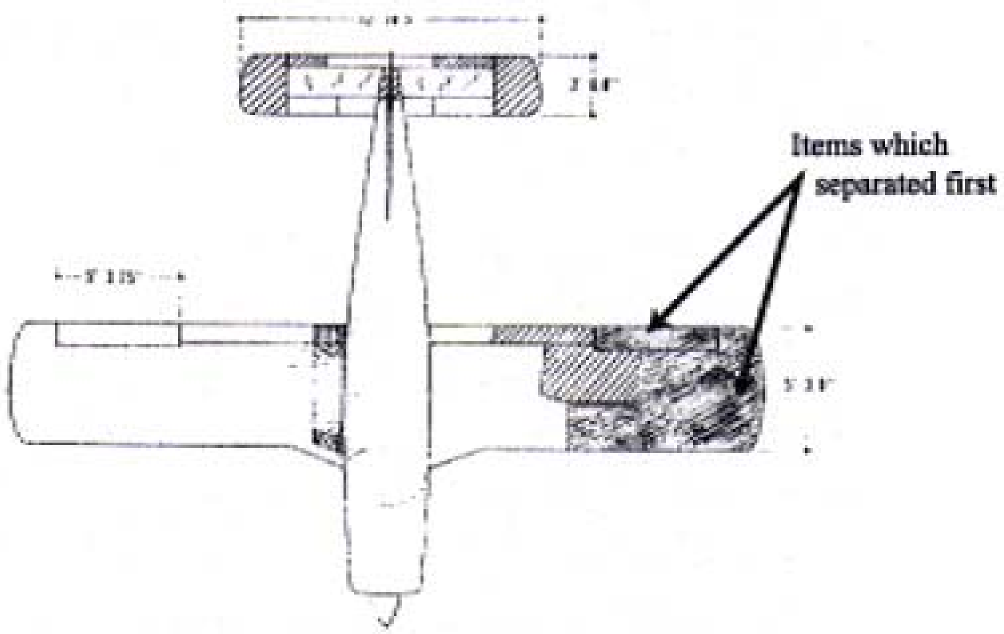


Diagram illustrating sections of structure which separted first, and subsequently, in-flight

The separation of the outer wing appeared to have been the result of excessive load applied in a downward direction. Interpretation of the radar data indicated that this had occurred within five seconds of the aircraft being in approximately straight and level flight. Despite the considerable effort devoted to detailed examination of the wreckage, in particular the airframe and flying controls, no technical failure was found in the wreckage which could have accounted for overload of the wing in such an unusual manner. Also, no evidence was found in the failed area of the wing of corrosion, fatigue cracking, repairs, material defects, or any other feature, which could have degraded the strength of the structure.

This aircraft was equipped with a roll axis autopilot and an electric pitch trim system and the possibility of related problems was considered. The rate of application of autopilot driven aileron deflection is relatively slow and limited by the design characteristics of the autopilot servo motor. It was considered highly unlikely, therefore, that this system could input a roll demand at a sufficiently high rate to compromise the structural integrity of the wing. Similarly, the pitch trim motor operates slowly and was considered unlikely to induce excessive wing loadings under, for example, a runaway condition.

Thus, in consideration of the above and in the absence of any significant weather factors, it became highly likely that an unusual control input, or inputs, could have precipitated the failure of the wing.

Aircraft design standards

Civil aircraft which are built in quantity, like G-BKCB, are required to have a Type Certificate before they may be used for purposes other than flight development. Issue of the Type Certificate may only take place after the aircraft type has been shown to comply with a set of design standards, the US Federal Airworthiness Requirements (FARs) in this case, which include structural strength requirements. These standards were evolved, largely empirically, over a lengthy period, for each class of aircraft and have remained largely unchanged for some decades. They are generally perceived, on the basis of accumulated experience, to be adequate and appropriate to the relevant aircraft classes to which they apply.

Aircraft are normally shown to comply with these standards by a combination of calculation and structural test to failure. Normally, the calculated positive (ie, upward in normal flight) loading of the wing structure, for the flight condition estimated to result in the lowest reserve factor (RF), is chosen for the final structural test. The RFs of the wing in downward loading are normally established by calculation. (The RF is the factor by which the actual strength of a structure differs from the strength needed to satisfy the certification requirements. This factor must always be greater than unity.)

Significant features of PA-28 Wing Structure

The wing of the PA-28 series aircraft is a structure of conventional riveted light alloy sheet skins and ribs, the former being supported/stiffened by widely spaced span-wise orientated stringers. The wing is assembled around a single main spar. This in turn is built in two parts. The inboard portion is a light-alloy 'I' section extrusion, of constant depth. Flanges on the aft face of the extrusion are progressively machined away from the inboard to the outboard end until at the outboard end the extrusion becomes a channel section. The outboard spar section is a pressed light alloy sheet component taking the form of a modified lipped channel overlapping and wrapped around the end of the extrusion, with the webs of the two elements extensively riveted together. The riveting forms a splice joint between the two elements. The edge flanges of the pressed outboard spar are joined to the flanges of the extruded spar, which they overlap, by means of a line of rivets which also attach the skins. The region of the splice joint therefore forms a step change in both shear and bending strength of the spar.

Other significant information

The design manoeuvring speed (Va) of the PA-28R-200-2 is 131mph (118 kts) EAS, whilst the dive speed Vd is 238mph (207 kts) EAS. The significance of Va in the design of an aircraft is that it is the maximum speed (EAS) at which the application of full control surface deflection, in one axis, will not overstress the aircraft. The FARs under which this aircraft was certificated, contain the following relevant requirements.

FAR Section 23.349

The wing and wing bracing must be designed for the following loading conditions:

(b) The loads resulting from the aileron deflections and speeds specified in 23.455, in combination with an airplane load factor of at least two thirds of the positive manoeuvring load factor used for design......

FAR Section 23.455

The ailerons must be designed for the loads to which they are subjected -

(2) (I) Sudden maximum displacement of the aileron control at Va...........

No requirements are stated to address the effects of sudden large deflection reversals of control surfaces.

The aircraft's flight handbook contains a section titled *Airspeed Limitations.* Under the heading *Manoeuvring Speed* the following is stated:

> *Manoeuvres involving an approach to the stall or full application of aileron or rudder control shall not be undertaken at a speed greater than 132 mph (115 kt).*
>
> *Although the aeroplane is strong enough for steady application of full rudder at this speed, a violently checked manoeuvre might overstress it. For example, any violent yaw must not be checked with sudden application of opposite rudder.*

The airspeed indicator colour marking for flight with the flaps retracted are given as:

> *Normal Operating Range 70 - 170 mph (61 To 148 kt) Green arc*
>
> *Caution Range 170 - 214 mph (148 To 186 kt) Yellow arc*
>
> *Never Exceed Speed214 mph (186 kt)*

Assessment of wing behaviour under load

The original design of the PA-28 Cherokee initial series and derivatives, including the PA-28R-200-2, was carried out more than 30 years ago. More accurate methods of stress analysis exist today than were available to the original designers. Since the downward separation of a wing is a highly unusual mode of failure, and the aircraft suffered this failure immediately after a period of straight and level flight, at or slightly below a typical cruising speed, an assessment of the wing behaviour under downward loading, in the known flight conditions and using available state of the art techniques, was carried out. As it was thought probable that control surface inputs induced loadings sufficiently high to fail the wing structure, attempts were made to evaluate the manoeuvres and resulting loads likely to create such a condition. It was of particular interest to establish whether unusually rapid application of control inputs could have had any unexpectedly severe effects on wing structural stresses.

Work was commissioned from a specialist company to produce a finite-element (FE) computer model of the wing structure, in the region of the failure point. Manufacturer's drawings provided limited dimensional data but, using this together with a sample wing from another PA-28R-200-2 from which detailed dimensions and thickness figures were gained, it was possible to generate the mesh of the FE model. Coupon samples were cut from corresponding spar and skin materials of another PA-28 series aircraft, withdrawn from service, which had been built at about the same time as G-BKCB. These were used to carry out tensile tests to failure and the ensuing stress/strain figures used as material data in the FE model.

The FE modelling programme produced coloured screen animations of the wing structural elements, with colour coding representing relative stress levels in different elements of the structure. These colours progressively changed as different stresses were calculated by the programme for increasing loading. The animation also showed local deflection and buckling of the mesh as failure took place. The structural analysis methods utilised were those used previously to analyse structural collapse, as experienced by occupied volumes and components of aircraft and vehicles involved in crash impacts, and were thus optimised to deal with rapidly applied loadings.

Aircraft control response analysis

A specialist in aircraft simulation studies was also engaged, to evaluate the behaviour of the aircraft under various time histories of pitch control input. He had extensive experience of utilising a simulator, capable of being programmed to represent characteristics of selected GA aircraft types, to carry out studies of pilot/aircraft interface issues on such machines. It was proposed to utilise data and programmes of the type normally used to drive this simulator, in order to assess behaviour of the PA-28R-200-2 under the flight conditions derived from the radar recordings and the meteorological after-cast.

From the examination of the wreckage, it was clear that the initial structural failure occurred in only the left wing. Hence, symmetrical overload of the wings was considered unlikely and thus a combined pitch and roll manoeuvre, resulting in asymmetric loading, most probably occurred. Since, however, an infinite combination of pitch and roll inputs was possible, it was decided to initially evaluate the behaviour of the structure under negative g symmetrical loading only.

A further specialist was engaged to modify an existing NASA developed mathematical model of a PA-28 series aircraft, to match the specific characteristics of the PA-28R-200-2 in preparation for its use in conjunction with the simulation programmes. Additional data not incorporated in the NASA model was derived from the relative dimensions and weights of versions of the PA-28 series and from wing section data relating to high negative angles of attack. A series of pitch control stabilator angle/time curve inputs were then applied by way of the simulation programmes to the developed model of the PA 28R-200-2.

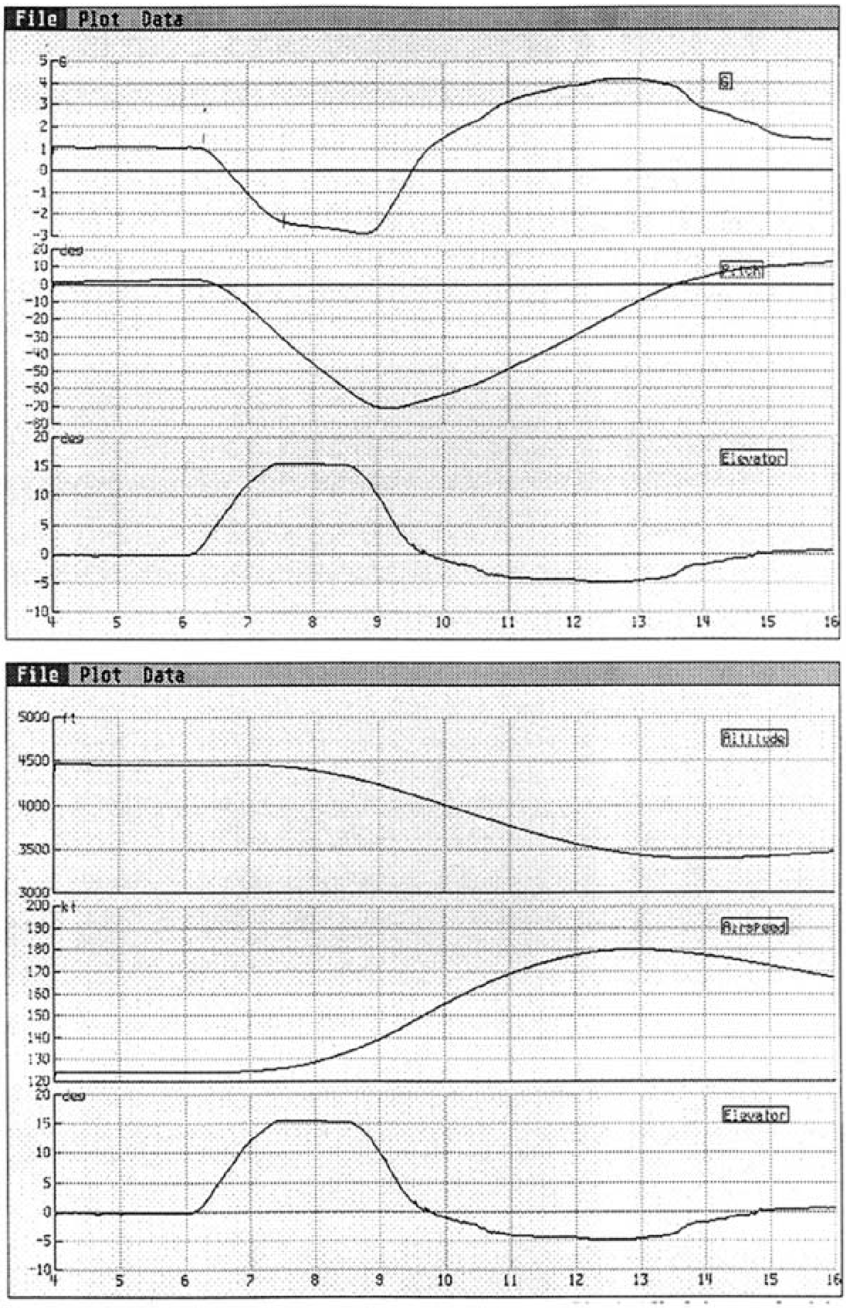
Initial figures of airspeed and altitude were utilised as the starting condition for the analysis of the manoeuvre. The flying control input curves were derived from experience of simulating this class of aircraft and were judged to be reasonable and achievable pilot inputs. Curves of stabilator angle, airspeed, altitude, pitch angle and normal acceleration were produced for a variety of short period stabilator angle/time histories.

Aircraft pitch behaviour

It was noted that a large, progressively applied, sustained input produced higher loadings than did a more rapidly applied, less sustained control deflection. In most cases, maximum negative g loading occurred before significant loss of altitude or gain of airspeed took place. One deflection/time history, Figure 4, produced a maximum normal acceleration of approximately -2.7g; this exceeded the design strength specified in the airworthiness code applying to the aircraft category. This time history was chosen and used to generate loadings which were applied to the FE model of the failing wing bay structure. It was noted that little change in EAS or altitude occurred before peak load was reached.

Figure 4

Figure 4



Calculated aircraft response - 15° stabilator angle for 3 seconds

100

Loading data for FE analysis

Loading data was produced by the specialist who developed the model of the PA-28R-200-2, in the form of non-dimensional span-wise and chord-wise lift distributions. (At high negative angles of attack the chord-wise centre of pressure was shown to migrate towards the leading edge as the wing-tip is approached.) Since the FE programme called for point loadings to be supplied as input data, these distributions were converted into a series of such loadings at discrete span-wise and chord-wise stations outboard of the plane of failure, assuming a -1g flight condition.

In order to conduct a preliminary check of the methodology, a position of a single point load was established which approximated to the mean position of the total loading outboard of the structural failure plane. A downward loading of steadily rising magnitude at this point was fed into the FE programme until simulated failure occurred. The failure initiated at a point very close to the same span-wise station as that observed on the accident aircraft.

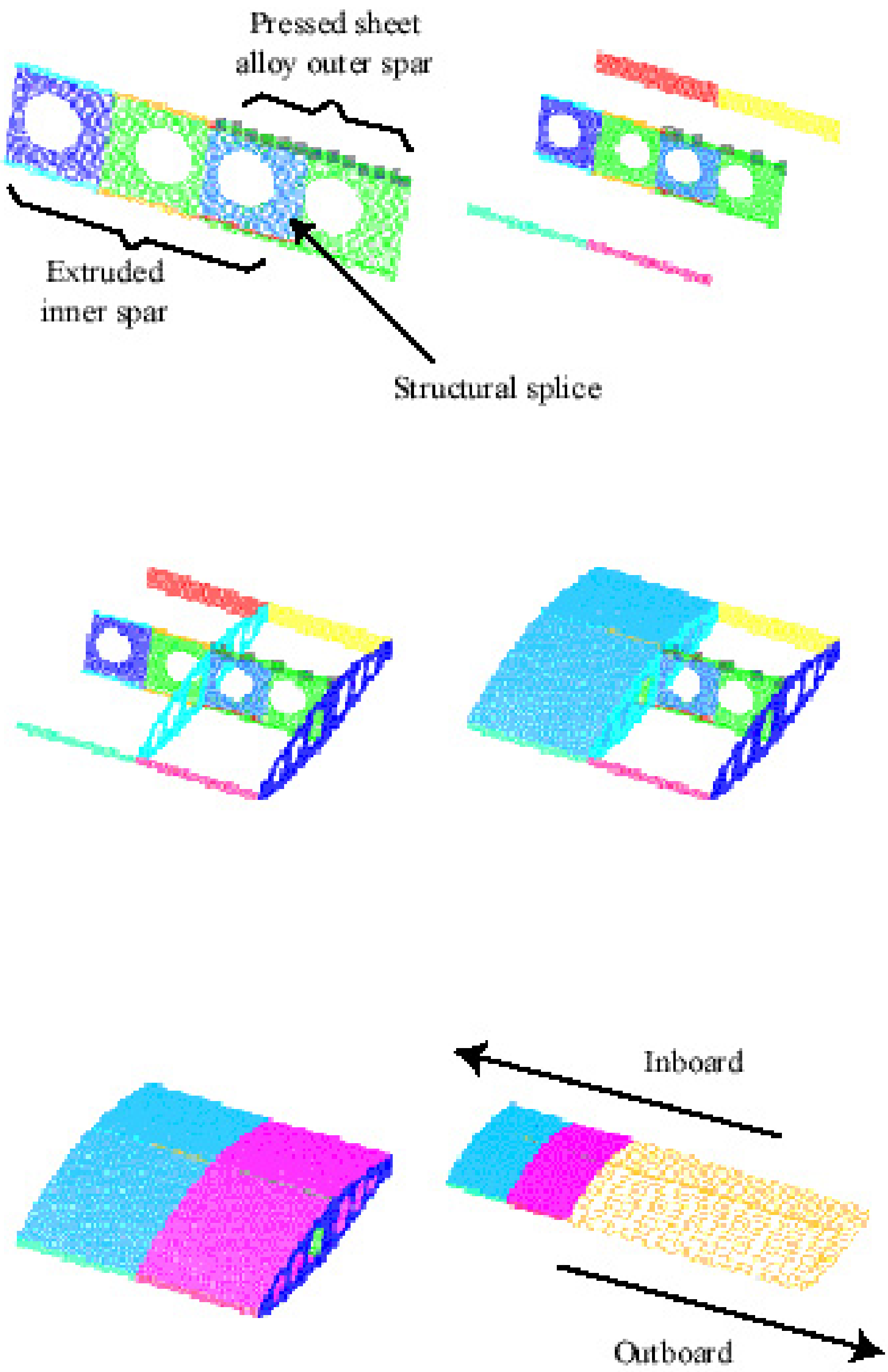
The FE animation of the initial buckling failure was studied. It was noted that most of the signs of buckling of elements of the structure seen to develop in the animation soon after the wing deflection became non linear, were also visible as permanent deformations in similar locations on the separated side of the actual wing hardware. Although the chord-wise position of the chosen load point was well forward of the wing spar, ie towards the leading edge, no significant torsional deflection was observed on the animation before the structure failed as a result of combined shear buckling in the spar web and compressive instability of the lower flange of the spar. The coloured stress representations also indicated that the torsional stresses (ie skin shear stresses) remained low as the spar failed in shear and bending. Similarly, no sign of torsional buckling or such failure of the wing structure was visible on the wreckage components. This exercise supported the initial observations during the wreckage examination that the outer wing failed and separated in download.

The normal acceleration/time history, derived from the analysis of the effects of forward yoke movement, was then used to factor the calculated point loads in order to evaluate the behaviour of the wing structure subjected to the fluctuating negative distributed loading of the manoeuvre. It was found that in the load condition in which -2.7g was reached, the FE model did not reach failure, nor did the coloured representations of stress levels shown in the animation suggest that failure was imminent.

In view of this unexpected result, the assumptions used in developing the FE model were reviewed. It was observed that restricting the model to a single bay had the effect of restraining the inboard boundary to remain in one plane and therefore caused the lower skin to provide a greater contribution to the compressive strength of the wing lower surface than would be the case with the actual aircraft structure. The FE model was therefore modified to incorporate a second bay inboard of the area of structure being analysed. This removed the assumed edge restraint of the skin panel in the FE model and allowed a more fully representative behaviour of the lower skin stiffness and compressive strength to be modelled. The geometry of the final FE model is shown pictorially in Figure 5.

Figure 5

Finite Element Analysis Visualisation



Build-up of structural components for Finite Element (FE) model

The loading/time history was then re-applied using twice the -2.7g figures. Once again, the FE model indicated that failure did not occur. Only when the loading was multiplied by 2.5 did the FE analysis show that failure occurred. In view of this second unexpected result of the analysis, doubt remained as to the validity of the FE model.

In order to resolve these anomalies, the wing behaviour under normal positive (upward) loading was therefore explored using the same FE model. This was compared with test data supplied by the aircraft manufacturer relating to an ultimate load test carried out in 1984 on this type of wing. (This was carried out some years after the constant chord wing design of G-BKCB had been replaced in production PA-28 series aircraft by a modified design having tapered outer sections.) The lift distribution calculated for the downward loading was used and applied in the reverse direction. Although the chord-wise distribution was considerably different for a wing operating in positive loading compared with the effect of the data so far used for a wing in negative loading, the span-wise loading distribution was judged to be not greatly different for the two load orientations. In view of the insensitivity to torsional loading described above it was judged that the incorrect chord-wise lift distribution would have little effect on the outcome. This exercise demonstrated the following;

- The wing bending strength and behaviour under positive g load predicted by the FE model was very similar to that demonstrated by the manufacturer's structural test.
- As a consequence, the method used to evaluate the downward loading effect in the previous analysis was judged to be valid.
- The wing bending strength in negative loading in the region of the splice was close to (and in fact greater than) the corresponding strength in positive loading.

Although the effects of symmetrical loading only had so far been considered, it was clear that the structural reserve factor in this part of the wing in the downward loading direction was very high. The increased loading at that station resulting from the effects of a deflected aileron on the down-going wing, during a simple combined pitch and roll manoeuvre, were not judged to be capable of raising stresses to the figure needed to fail the wing.

Other possible classes of manoeuvres

At this juncture, advice was sought from specialists in manoeuvring loads on military combat aircraft. It was pointed out that high structural loads can be generated by carrying out a 'checked' manoeuvre, ie, one involving the application of large control deflections, followed almost immediately by their (large deflection) reversal.

In order to evaluate such effects on an aircraft such as G-BKCB, a company with considerable experience in dynamic modelling of aircraft behaviour, was engaged. They developed a comprehensive three dimensional computer model of the PA-28R-200-2, using measured dimensions and known aerodynamic characteristics to generate a NASTRAN/PATRAN aerodynamic model. This was used to establish longitudinal and lateral coefficients for the aircraft. Estimated mass distribution figures were produced by scaling down known data from a four seat aircraft of similar general layout and proportions. A six degree of freedom model was generated in SIMULINK. The model flies the aircraft for the ascribed conditions and manoeuvres, and generates the forces and moments at specified monitoring points on the aircraft structure. Graphs of time histories of the following parameters were produced:

Control surface deflections (assumed occupant inputs to the control yoke)

Altitude and airspeed (beginning with the starting conditions derived from radar data and the meteorological aftercast)

Pitch roll and yaw angles

Rate of change of pitch/roll/yaw angle

Angle of attack

Sideslip

Accelerations

Shear forces and bending moments at specified points on the wing of the model.

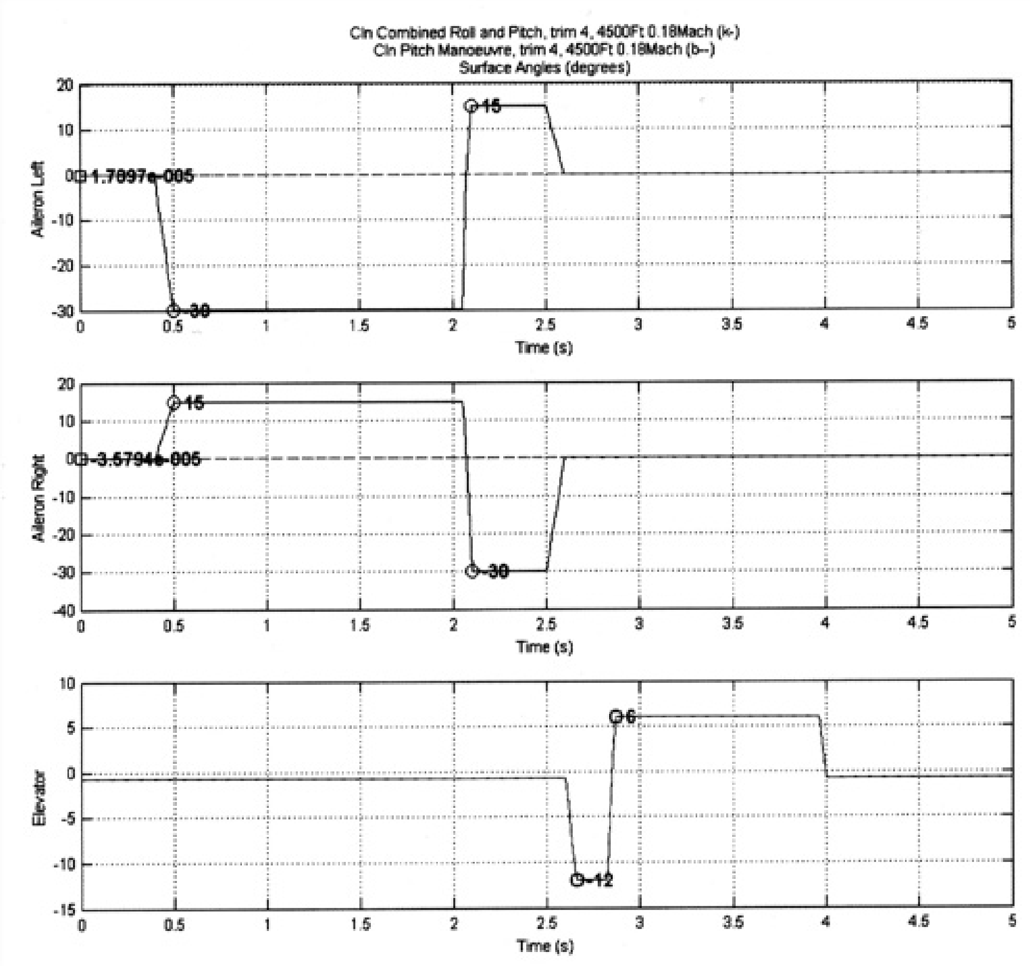
Manoeuvres investigated in detail

It was suggested that an inadvertent large movement of the control yoke could have been applied, in both pitch and roll, followed immediately by a large movement correction (ie, a reversal). Therefore, a time history of simultaneous stabilator and aileron deflections was developed and applied to the computer model, again using the airspeed and altitude conditions at entry, derived from the radar recording and the wind data available from the meteorological aftercast. The first manoeuvre evaluated began with a full forward movement of the column, accompanied by a full lateral aileron deflection thereafter followed by full aileron deflection in the reverse sense and full backward movement of the column, all applied with overlap. The computer programme used calculated, using the simulated aircraft motion parameters, the shear-force and bending moments at a series of span-wise stations of the wing spar. The loading was found to vary a number of times, with time, through a considerable range, before rising to high shear force and bending moment figures.

The peak bending moment generated at the failure station was used in conjunction with simplified cross-section dimensions and second moment of area calculations to establish tensile and compressive stresses at the edges of the pressed alloy outer spar. These were found to be well in excess of the yield stress for the material. These figures were reached some three seconds after the start of the first input. It was clear therefore that this combined manoeuvre would comfortably achieve bending failure of the wing structure. Analysis of this result, however, revealed that the high loading occurred in a direction that would cause the wing to fail in 'upload', but all the evidence from the wreckage indicated that failure had occurred in download. The analysis of behaviour of the computer model was therefore repeated using a different time history of control deflections. The new history began with backward column movement and roll input, followed by reversal of aileron deflection directions and forward movement of the column.

During this analysis, some errors were noted in some assumptions used to generate the high forces in both the manoeuvre sequences, ie, those producing high loads in both the upward and downward directions. With some corrections and refinements in the computer model, however, it proved possible to demonstrate that with certain initial trimmed conditions, very high loads in a downward bending direction could be developed using the sequence of control inputs shown in Figure 6.

Figure 6



Control input sequence which resulted in very high wing loads
in a downwards direction

These involved use of full available control deflection in both pitch and roll, and the resulting aircraft manoeuvres are illustrated in Figure 7.

Figure 7

Figure 7

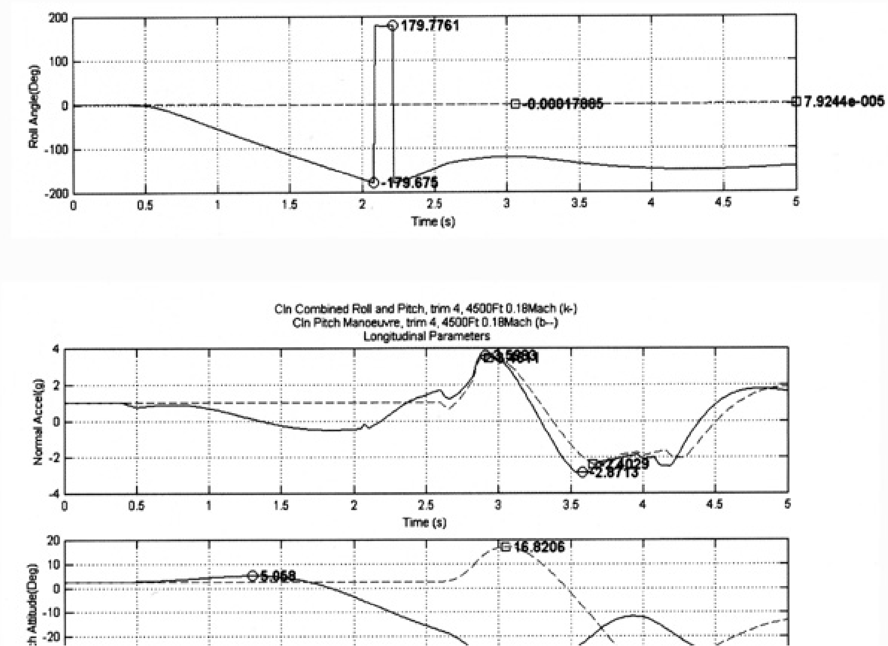
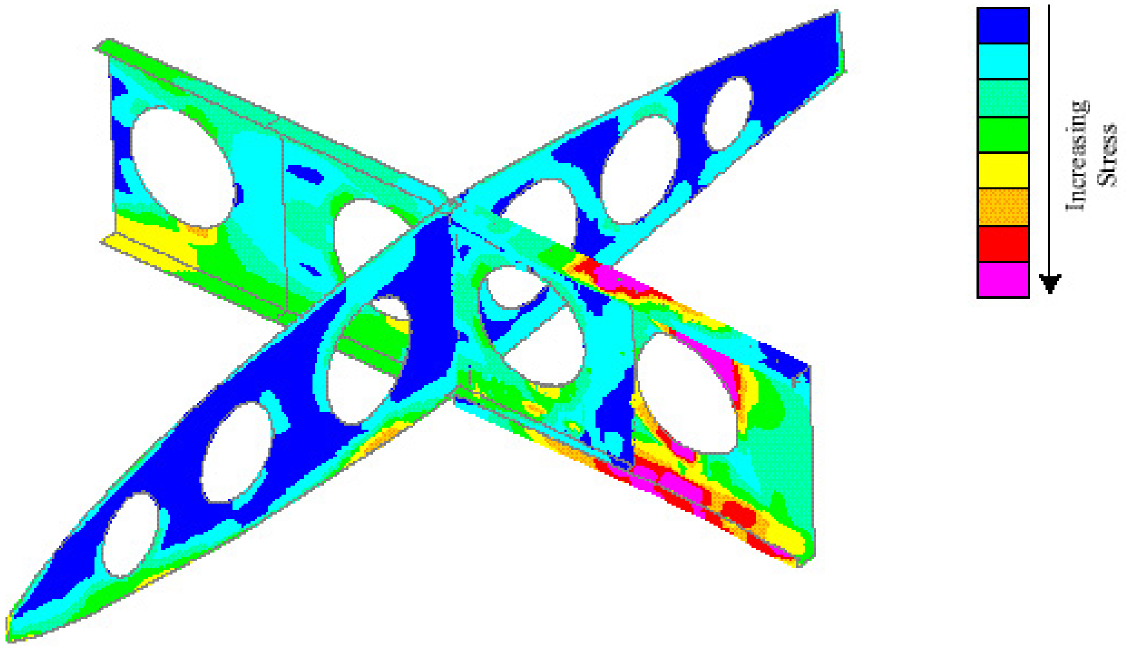
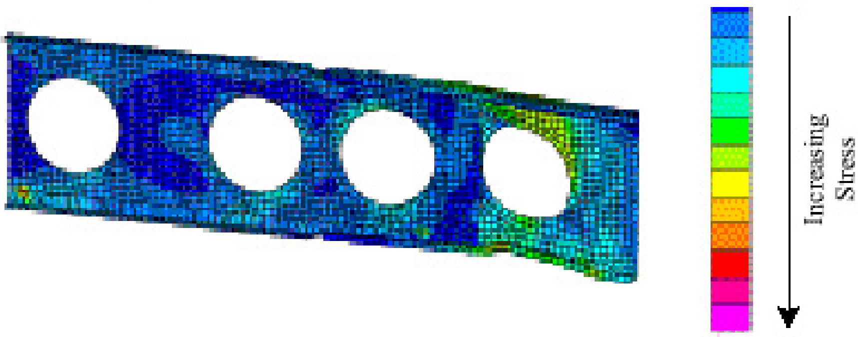


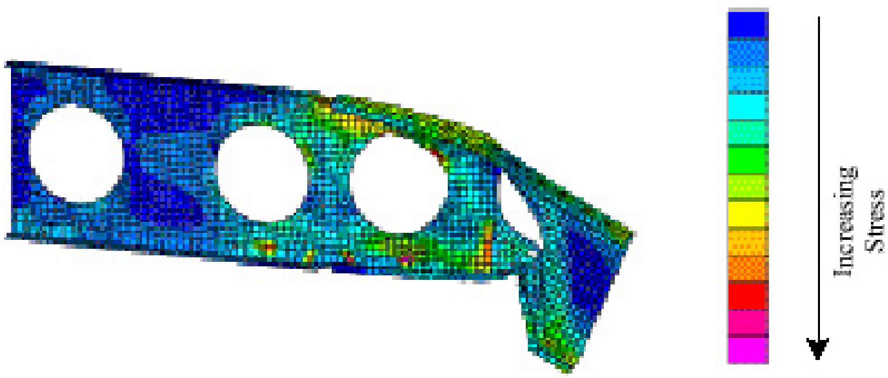
Figure 9b

Finite Element Analysis Visualisation of Internal Structure



Progressive buckling of spar





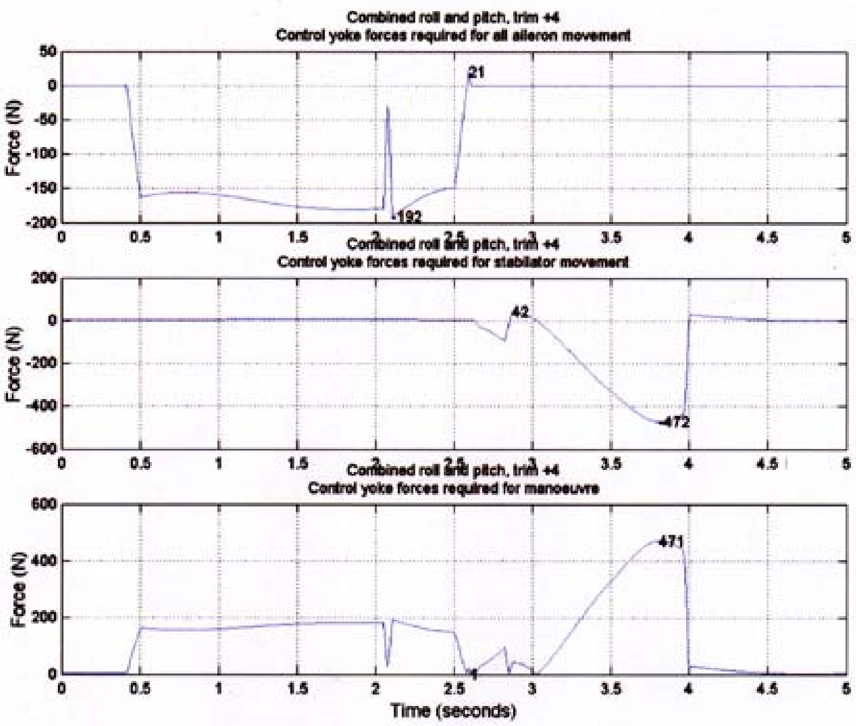
It is likely that a number of slightly different combinations of pitch and roll control inputs, having similar total duration but slightly differing spacings, could be developed, resulting in stresses being generated at the failure plane having comparable magnitude to those realised in the above case. It was noted that the shear force and bending moment figures, presented for the trimmed flight condition at which failure load was approached, were computed specifically for the span-wise station at which wing separation occurred. Re-examination of both the failed structure and the FE results show that initial failure began very close to the end of the extruded inner spar, rather than at the more outboard point of final separation. Shear force and bending moment curves against time were presented for the manoeuvre at a range of span-wise stations. Interpolation showed that the bending moment at the initial failure station was approximately 30% greater than at the point of final separation.

Hence, although the precise structural load condition at which failure would have occurred was only computed approximately, there was little doubt that some combination of rapid pitch-up and roll inputs, followed by rapid control reversal, using control movements to approximately full available travel, could have failed the structure at the airspeed applying at the time the aircraft departed from normal flight. The analysis also shows that the loading to reach failure would readily be achieved in the short period available between the time when the aircraft was in level, unaccelerated, flight and that at which structural debris separated from the aircraft, as indicated by the radar recording.

Calculated Control Forces

The control yoke pitch and roll force/time histories required to achieve the surface deflections assumed in the analysis are shown in Figure 10. These were calculated from the hinge moments produced as part of the NASTRAN/PATRAN analysis and the geometry of the control system, calculated by measurement of control surface angles and corresponding control yoke travel on an example of the aircraft type. They did not take account of frictional losses in the control system.

Figure 10



Control forces predicted to achieve wing failure

A precise analysis of control force capability by individuals of particular body weights and strengths was not carried out. Control forces defined in the FARs as acceptable for certification were, however, reviewed and can be compared to give some assessment of the capability of the occupants of G-BKCB to achieve the forces needed to create the structural shear forces and bending moments predicted.

The significant sections of the FARs show that a maximum of 75 lbf in pitch, and 50 lbf in roll, is permitted, using both hands for temporary application whilst, with one hand, the figures are 50 lbf and 25 lbf respectively. Control is a delicate activity requiring precision, only possible if the required force is well below the physiological maximum force capable of being exerted by a person of average or below average strength. Hence, most individuals would be capable of briefly exerting considerably higher forces than those quoted.

The peak control yoke force indicated by the analysis as necessary to achieve the manoeuvre described above is 43 lbf in roll, ie significantly above that permitted by the FARs for roll control with one hand but less than that required when using both hands. The peak control force required during the second, or 'recovery', phase of the manoeuvre was far greater, being 105 lbf in the pitch sense. This is above the figure of 75 lbf for temporary use of both hands specified in the FARs.

The analysis of the control forces also showed the initial pitch force figure required to maintain level flight in the various trimmed conditions studied. It makes it clear that a control force of one lbf or less is required to maintain level flight at the trim tab settings assumed in the final analysis, to enable the predicted shear forces and bending moments for wing failure to be achieved.

Analysis

G-BKCB had accumulated nearly 4,000 flying hours since it was built in 1974, and there are many examples of PA-28 still flying with the same wing type as fitted to this aircraft. From the wreckage examination, no evidence was found of any pre-existing defects in the aircraft generally, or in the region of the wing failure in particular, which could have accounted for any degradation of the strength of the 'as designed/manufactured' wing structure. In consideration of these facts, it was therefore thought highly improbable that any basic design, manufacturing or in-service defect(s) had been associated with the failure. Thus, in the absence of any known wake vortices or significant weather factors, it was considered most likely that an unusual control input, or a combination of inputs, had precipitated the failure of the wing.

Normally, on non-instructional flights, control inputs would be applied by the pilot. On a sightseeing/pleasure flight with passengers, at least two of whom were thought to have been unused to flying in light aircraft, it was considered very unlikely that the pilot would have voluntarily indulged in violent and extreme control inputs. There was evidence, however, to indicate that extreme manoeuvring had taken place just prior to the in-flight break-up. This evidence took the form of the absence of a secondary radar return at time 1502:10, followed by the presence of a return (at a slightly lower altitude) at time 1502:14. This suggested that the transponder antenna, positioned on the underside of the aircraft, was shielded from the secondary radar head at the earlier time. It is more likely, therefore, that the aircraft had briefly diverged from a level roll and/or pitch attitude, probably approaching or achieving an inverted position and hence masking the transponder antenna, rather than a temporary malfunction of the secondary radar system having occurred. Four seconds later, the aircraft appeared to have returned to an attitude at which the antenna was again unobstructed although, from the presence of multiple primary radar returns at that time, the aircraft had already suffered the wing failure.

The mean ground-speed derived from the radar recording for the period of level flight following time 1501:54 corresponded to an EAS of approximately 112 kt, assuming zero wind. The aftercast suggested that the mean wind at the altitude of the aircraft during this period was approximately at right angles to the aircraft track, so it is reasonable to assume that the aircraft EAS was close to 112 kt as the aircraft passed point No 4 on the radar plot. This suggests that the aircraft was flying at or just below the design manoeuvring speed, Va, of 118 kt. The airspeed indicator (ASI) markings on this class of aircraft incorporate a green sector up to the normal operating limit speed, Vno, and a yellow caution range up to the never exceed speed, Vne. These speeds are, however, associated with cruising flight in varying conditions of atmospheric turbulence and are not intended to have any relevance to the deliberate manoeuvring of the aircraft. Va is not customarily marked on the ASI, but is to be found in the aircraft's Flight Manual.

The series of primary returns following time 1502:10 are orientated downwind and were almost certainly from items of separated structure drifting NNE whilst falling. Their point of origin, located on the plot by the intersection of the mean line through the primary radar returns and the line of the secondary radar track, Figure 1, lies close to the position where the absent secondary radar return would be expected to lie. This suggests that the break-up began during a brief period that the aircraft was not level in pitch and roll. The plot also indicates that both the change of aircraft orientation and the first structural failure occurred no more than five seconds after the aircraft was in level unaccelerated flight. The only feasable sources of control surface movement considered to be able to cause this extreme manoeuvre were either, control yoke inputs being applied by the aircraft occupants or, inputs generated by the auto-pilot.

This aircraft was only equipped with a basic roll axis auto-pilot and had an electric pitch trim system operated by a yoke mounted switch. A single point failure that could cause uncommanded operation of both pitch and roll control systems was considered unlikely, and it was not possible to visualise a defect or failure which could lead to a rapid full control deflection, in either axis, followed closely by a control reversal to full travel in the same axis. In addition, the auto-pilot servo had limited power and operating speed which would prevent it from applying high rates of change of aileron angle whilst the designed slow rate of operation of the pitch trim actuator would similarly limit the rate of change of stabilator angle.

The possibility was considered that some form of roll servo motor runaway, initially resisted by the pilot, may have caused a rapid roll input to occur should he release the column with a built-up tension present in the auto-pilot bridle. Although this could be very disconcerting to an average low hour PPL holder, the actual resulting aileron rates of application would not approach the figures used in this analysis and cannot readily explain the cause of the full sequence of control movements required to load the wing to a download failure condition.

The precise actions carried out by the aircraft occupants in the two front seats in the seconds before the structural failure occurred can only be a matter of conjecture. Although the pilot and passengers were not observed taking their places in the aircraft, it is reasonable to assume that the pilot occupied the usual front left-hand seat of the dual control aircraft and that the young child occupant, who was found in the rear of the cabin, would sit alongside her father. This would make it most likely that the front right hand seat occupant was the person not known to the pilot but the close adoptive relation of those seated in the rear. Although the pilot and his work colleague were both employed as aircraft maintenance personnel with major airline companies, the work colleague's relative had not been employed in, nor had any particular involvement with, or knowledge of, aviation, so far as could be established.

One scenario considered possible for the inadvertent application of extreme control inputs, was as follows. It is not known if the rear seat occupants wore headsets but it would be possible at some point in the flight for the front right seat occupant to have turned round and /or leaned back to communicate with his relatives in the rear. In doing so, or in turning back to face forwards, it is possible that he may have inadvertently grasped one side of the control yoke in front of him. Such an action could have readily resulted in the yoke's longitudinal or rotational movement, or a combination of both, with or without a time overlap. With the aircraft in steady trimmed level flight, without turbulence, the pilot would reasonably have been expected to have been holding the controls very lightly, and may have even been flying 'hands-off'.

Analysis of the directions of roll movement of the yoke shows that it must be initially rotated to the left to produce the sequence of responses necessary to conclude with the downward failure in the left wing, Figure 8. Thus, grasping the right hand horn of the yoke, possibly using it as a 'handhold, could have resulted in the direction of roll input and movement (coupled with some pitch-up) required to initiate the calculated sequence to fail the wing. It would be reasonable to assume in this scenario why an alarmed occupant, finding himself being rolled very rapidly to the left, and tending to fall towards the pilot whilst possibly experiencing highly unusual sensations and not understanding, might, understandably, tend to hang onto the control horn and accentuate the problem. It is also reasonable to assume that, under such circumstances, a person would be able to exert considerably more than the maximum 25 lbf, the figure defined by the FARs to control an aircraft in roll.

The 'recovery' manoeuvre would be the natural reaction of a pilot who, within the space of 1.5 seconds, probably found the aircraft inverted, subjected to negative g forces and having undergone a 30° pitch change. For certification, the FARs allow for up to 75 lbs to be applied briefly to control an aircraft in pitch, using both hands; hence a pilot of above average size and (probable) strength and faced with a serious situation, would likely be able to briefly apply 105 lbs or more to the yoke to complete the 'recovery' manoeuvre and induce loads in the wing needed to cause structural failure.

The initial achievable roll rate in this scenario is very high and, if the pilot was not expecting it, he would be unlikely to immediately regain an effective grasp of the yoke. The output of the modelling programme showed that with the assumed rate of initial control input, the aircraft becomes effectively inverted within 1.6 seconds, whilst the normal acceleration experienced by the occupants falls below zero within 1 second. This reaches -0.5g within 1.5 seconds. The natural reaction of a pilot in this circumstance would be to rapidly apply roll control in the opposite direction to that already applied, in an attempt to return the aircraft to straight and level flight; his reaction in the pitch plane would be harder to predict. Considerable pitch change in a control yoke aft sense could readily have been applied by either the passenger or the pilot in this scenario.

At some stage, the intervention of the pilot would probably have become effective. As the aircraft could have been approaching an inverted position, the direction of his reaction in pitch is unlikely to have been intuitive and may have initially opposed the direction of the yoke aft condition already applied. Alternatively, his reaction may have caused the initial aft movement of the yoke. Either way, he may have rapidly reversed the longitudinal position of the yoke in a state of understandable confusion. Such a sequence of control movements has a close similarity to those postulated in the analysis above. Thus, the possible combined actions of the two front seat occupants described above could, reasonably, account for the highly unusual structural failure of the wing immediately after a period of straight and level flight.

Other possible scenarios, resulting in the sequence described above, were those of allowing the controls to be (mis)handled by a person with no known piloting experience or training, or that the pilot or front seat passenger became incapacitated, or that the passenger became anxious/frightened and grabbed the controls.

Although these scenarios and the set of actions described above are a matter of conjecture, the specialist responsible for the analysis observed that if the general combination of rapid control movements and reversal is carried out in the two control axes, variation in overlap between the pitch and roll inputs results in only a very small reduction in resulting structural loads. Similarly, the rate of initial control input can be reduced slightly and rendered non linear without greatly altering the final loads generated. Thus, any sequence of control inputs similar to that described above would have put the aircraft wing at risk of a structural failure. It is generally well known amongst pilots that excessive control inputs are capable of leading to structural failure of aircraft. It is, perhaps, less well understood that large control surface deflections, applied simultaneously or in rapid sequence in more than one axis, are far more damaging than such inputs applied individually. When such single or multi-axis inputs are applied and rapidly reversed, even higher loadings result. Although the manoeuvre speed, Va, is described as the speed above which full deflection of aileron or rudder or approach to the stall should not take place, it may not be appreciated amongst all pilots that flight at airspeeds below Va does not provide protection from control induced structural failure. Should excessive simultaneous and/or reversed large control deflections be applied, the results can be catastrophic, as in the case of G-BKCB. This is all the more significant when it is noted that the structural strength of the wing of this aircraft type in download, far exceeds the requirement specified for its certification.

Conclusions

Despite a lengthy and detailed investigation, no evidence of any external factors or pre-existing defects within the structure or the flying control systems was discovered which could have explained the unusual structural failure of the aircraft. Only a sequence of highly unusual, control induced, manoeuvring would be consistent with all the evidence available. The investigation did not reveal any evidence that the possibility of such a sequence of control inputs had been a deliberate action, or that the manoeuvre could have been induced by any reasonable failure of the auto-pilot or pitch trim system. Thus, the manoeuvre being unintentionally initiated by, possibly, the front right seat occupant grasping the control yoke for support, and completed by the pilot in an attempt to recover the aircraft, could not be dismissed.

The result of this manoeuvre, within some five seconds of the aircraft departing from normal flight, was the downward separation of the outer section of the left wing and loss of the left aileron. Other major parts of the aircraft separated as it reached high speed in the subsequent descent. The analysis of this event indicated that the initial failure took place before significant increase in airspeed or loss of altitude occurred. The theoretical analysis of the structural design indicated that the strength of the wing in download, at the point of failure initiation, greatly exceeded the minimum requirements of the type certification documents. It also showed that the failure of the wing, in the mode which occurred, could be induced at an airspeed at or slightly below the manoeuvre speed, Va, only if a sequence of rapid full control surface movements and reversals took place, near simultaneously, in the pitch and roll axes.

Safety Recommendation

This aircraft, in common with other type certificated aircraft, would have complied with the certification requirements in the sense that full deflection of a single control at or below Va would not overstress the airframe. Some consideration is given to the combined application of full aileron in conjunction with a positive load factor, in FAR part 23.349, but no consideration is given to such cases as large deflection control surface reversals, in combination with positive and negative normal load factors, which can induce damaging stresses in the wing at or below Va, as was highly likely the case here. This is due to the fact that there are many combined control input scenarios that may cause damage or failure, but these are considered to be relatively unrealistic cases for aircraft such as the

It is not known if the pilot of G-BKCB fully understood the significance of Va. Any serious departure from controlled flight, for whatever reason, would probably trigger an instinctive reaction by most pilots to rapidly 'recover' the situation, with the attendant risk of damaging or failing the aircraft structure, without immediate regard for the significance/limitations of the manoeuvre speed. Although most pilots of aircraft types such as the PA-28 would not intentionally apply extreme control inputs, this accident does highlight the fact that flying at or below manoeuvre speed does not provide protection of the aircraft from damaging stresses for all possible manoeuvres.

It is therefore recommended that:

Safety Recommendation 2003-98

The CAA should review the current training syllabus for the Private Pilot's Licence and the literature available to pilots generally, with respect to raising the awareness of the significance of manoeuvre speed, and clearly make it known that flying at or below manoeuvre speed does not provide protection for the aircraft structure from damaging stresses for all possible combinations, and reversals of, control inputs.