ACCIDENT

Aircraft Type and Registration:	Zivko Aeronautics Inc Edge 540, N540BW
No & Type of Engines:	1 Lycoming AEIO-540 piston engine
Year of Manufacture:	1998
Date & Time (UTC):	22 August 2009 at 1057 hrs
Location:	Silverstone Circuit, Towcester, Northamptonshire
Type of Flight:	Competition
Persons on Board:	Crew - 1 Passengers - None
Injuries:	Crew - 1 (Fatal) Passengers -N/A
Nature of Damage:	Aircraft destoyed
Commander's Licence:	FAA Commercial Pilot's Licence
Commander's Age:	41 years
Commander's Flying Experience:	2,500 hours (of which 1,400 were on type) Last 90 days - 50 hours Last 28 days - 11 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft was being flown in an aerobatic competition during which it failed to recover from a downwards snap roll manoeuvre, initiated at about 2,300 ft agl. The aircraft continued to rotate until it struck the ground, fatally injuring the pilot. The investigation discovered a mechanism whereby rudder pedal extensions used by the pilot could have contributed to a rudder control restriction, but pilot incapacitation was also considered a possible contributory factor.

Background to the flight

The pilot was a competitor in the 25th World Aerobatics Championship, being held at Silverstone racing circuit over a 10 day period in August 2009. She was a member of the US aerobatic team and had arrived in the UK several days before the competition was due to start.

N540BW was based in the UK and the pilot had arranged with its owner to use the aircraft in the competition. On 12 August 2009 she ferried the aircraft from Old Sarum Airfield, near Salisbury, to Dunkeswell Airfield in Devon, where the US team were conducting their final practice flights. Competition flying started at Silverstone on 21 August, beginning with qualifying flights. The pilot was drawn approximately halfway down the list of competitors, so her first flight in the competition was on 22 August.

Each pilot had a 10 minute slot in which to complete a set sequence of nine aerobatic manoeuvres. The length of the slot normally allowed a short practice session before commencing the sequence proper – indicated to the judges on the ground by a wing waggle (radios were fitted but silent procedures were in use).

The aerobatic sequence was to take part within an area of sky known as the 'box', with penalties for aircraft going outside the box during the sequence. The box had a ground footprint of one square kilometre, marked on the ground by orange panels. The lower vertical limit was 120 m (394 ft) agl and it extended upwards to 1,000 m (3,280 ft) agl. The box was aligned with the runway at Silverstone, and set approximately 50 m to the south-east. Judging positions were established a short distance outside the box, on its main axes. A plan of the site, showing the box area and accident site, is at Figure 1 (courtesy Google Earth ™ mapping service/ Tele Atlas, Infoterra Ltd & Bluesky).

History of the flight

On 22 August 2009 flying started at 0800 hrs with a weather check flight. This was followed by the first competition aircraft at 0818 hrs. Low cloud then interrupted the programme, with competition flying resuming at about 1000 hrs. N540BW, which had been kept in a hangar since its arrival at Silverstone, was the fifth aircraft to fly, taking off at 1048 hrs.

On this occasion, the pilot initially flew the first five manoeuvres as a practice before signalling to the judges that she was starting the sequence proper. After one manoeuvre, the pilot signalled that she was interrupting

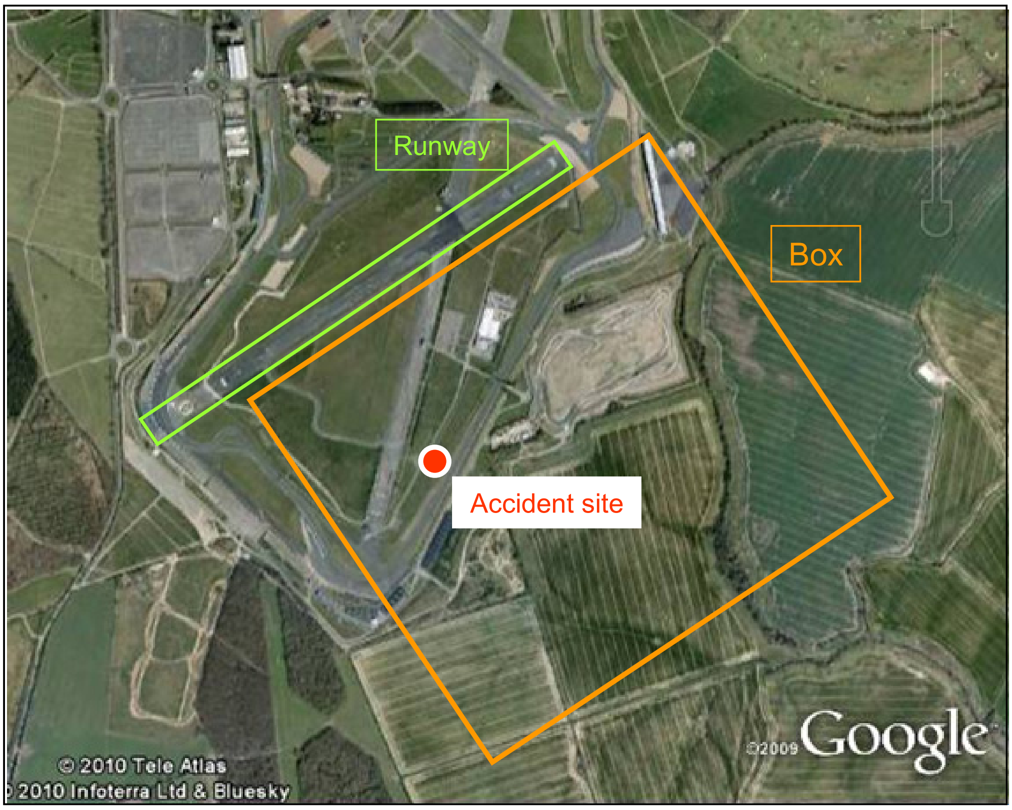


Figure 1

Part of Silverstone circuit showing runway, aerobatic box and accident site the sequence, which was allowed under the rules. About a minute later, the pilot restarted the sequence at manoeuvre two.

The accident occurred during the fifth manoeuvre of the sequence, which was the last manoeuvre the pilot had practised minutes beforehand. The manoeuvre called for a pull up to the vertical, followed by half of an eight point roll (rolling through 180°). The aircraft was then to be 'pushed over' the top of the manoeuvre until it was pointing vertically nose down, before carrying out a positive snap roll[1] to the left through 1¼ turns and pulling out to the horizontal.

The aircraft appeared to perform the initial stages of the manoeuvre normally but it did not recover from the downwards 1¼ snap roll. Instead, the aircraft continued to rotate in a nose-low attitude until it struck the ground.

Airfield staff immediately alerted the circuit race control (motor vehicles were using the race track at the time) and the emergency services. The circuit's own emergency response plan was activated and joined by local police, fire and ambulance services. The pilot was found within the wreckage having suffered fatal injuries.

Wreckage

The wreckage was located within the race track (Figure 1). The wing tips and the engine had struck the ground at an angle of approximately 45°, with the aircraft in a nose down attitude and the left wing being more damaged than the right. The aft fuselage and attached empennage had separated from the wings and forward fuselage, and these two major items of wreckage were located 10 m apart. Smaller items of wreckage were spread over an area approximately 80 m x 30 m, with the majority of the items located beneath the aircraft's final flight path. It was concluded that the aircraft had struck the ground in a nose-down, left wing-low attitude with significant rotation, and that, when the aft fuselage broke from the forward fuselage, parts of wreckage were thrown back along the flight path. All the major items of the aircraft were accounted for and there was no evidence of an in-flight break-up.

There were chordwise witness marks on the propeller blades, the lower blade of which had dug into the ground with a helical motion. It was concluded that the propeller was rotating under power when the aircraft struck the ground.

The air speed indicator had been damaged, with the needle and the face distorted. The needle was pointing at 130 kt.

Aircraft information

The Zivko Edge 540 is a high-performance single-seat aerobatic aircraft, see Figure 2. The wings and empennage on N540BW were made of composite

Figure 2

Photograph of N540BW
(photograph courtesy of Stuart Carr)

Footnote

1 Also called a flick roll.

material, and the fuselage was constructed from tubular steel covered in a mixture of fabric and composite material.

Figure 3
Cockpit layout

Figure 3 is a photograph of the cockpit layout. The control column was connected to the ailerons and elevators by a series of conventional pushrods and bell cranks. The rudder pedals were mounted on light alloy footplates which were attached to horizontal tubular steel fuselage cross-members. On the outer side of each pedal was a connection to a cable that ran rearwards to the respective rudder control horn. Also connected to the side of each pedal was a light spring that ran forwards and was attached to the fuselage structure. These springs prevented the rudder pedals from falling rearwards when no foot pressure was applied. The rudder pedals were operated with the pilot's heels on the foot plates and the balls of their feet pushing against horizontal tubes on each pedal. The aircraft was fitted with adjustable foot straps which passed through these horizontal tubes. When used, they ensure that the pilot's feet remain in contact with the rudder pedals; they also allow the opposing foot to pull at the same time as the other foot pushes. The range of movement of the rudder cables was ±45 mm, producing rudder deflections of ±30°.

Rudder pedals

The pilot was the owner of another Edge 540 which was based in California. She was 5' 2" / 1.57 m tall and flew her Edge 540 with extensions fitted to the rudder pedals. Prior to her first flight in N540BW, she had a set of her own pedal extensions fitted to the aircraft (see Figure 4). Each extension had been secured at its lower attachment around the pedal pivot tube by a pip-pin. The upper attachment consisted of two tie-wraps fitted diagonally around the horizontal tubes against which the balls of the feet would normally be placed. The pilot did not use the adjustable foot straps, which remained with the rudder pedals.

The pilot had experienced a problem whilst carrying out a snap roll during practice. During the manoeuvre

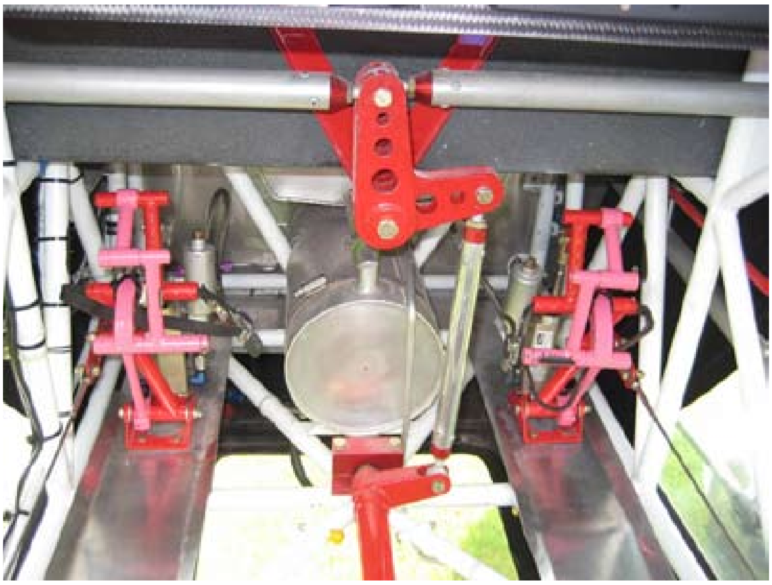


Figure 4
Rudder pedals with pedal extensions (pink) fitted

her right foot had bent the right foot plate downwards, deforming it. The footplate was straightened after the flight. The team engineer prepared a pair of longer, stiffer footplates but these had not been fitted at the time of the accident.

According to information posted by the pilot on her internet site, another pilot had also bent the footplate, whilst getting into the aircraft, and had bent it back. The photograph at Figure 4 shows the right footplate with evidence of the deformation. It is not known if this was taken after the ground or the airborne incident.

Aircraft certification

The aircraft was registered in the USA and had been issued with a FAA *Special Airworthiness Certificate*. It was classified as *Experimental – Exhibition* and the CAA had issued an exemption form for its use in the UK. This category of aircraft is not required to conform to any FAA approved type design and FAA approval was not required for the rudder pedal extensions. The FAA does not consider that pedal extensions are a modification to a primary flying control.

Wreckage examination

The wreckage was recovered to the AAIB for further examination. The elevator and aileron systems were checked for continuity as well as for full and free movement; nothing significant was revealed. The rudder surface operated with full and free movement, but the left and right cables were found to have failed in overload.

Detailed examination of rudder pedal assemblies

Both rudder pedal assemblies (see Figures 5 and 6) were taken to a forensic laboratory for detailed examination.

The following observations were made:

a) The lower attachment of the rudder pedal extensions could be moved in a spanwise direction along the rudder pedal pivot tubes (see Figure 7).

b) In the case of the non-extended rudder pedals, the force applied by a foot acts directly above the point at which the vertical element of

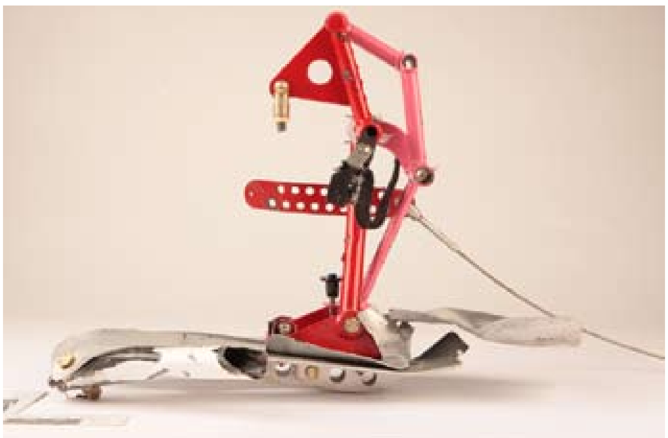


Figure 5

Right rudder pedal with extension

Figure 6

Left rudder pedal with extension

the pedal meets the pivot tube. This is due to the Z shape of the pedal. However, with the pedal extensions, the force applied by a foot acts inboard of the point where the vertical extension element meets the lower attachment, potentially creating a moment that can push the lower attachment outwards along the pivot tubes.

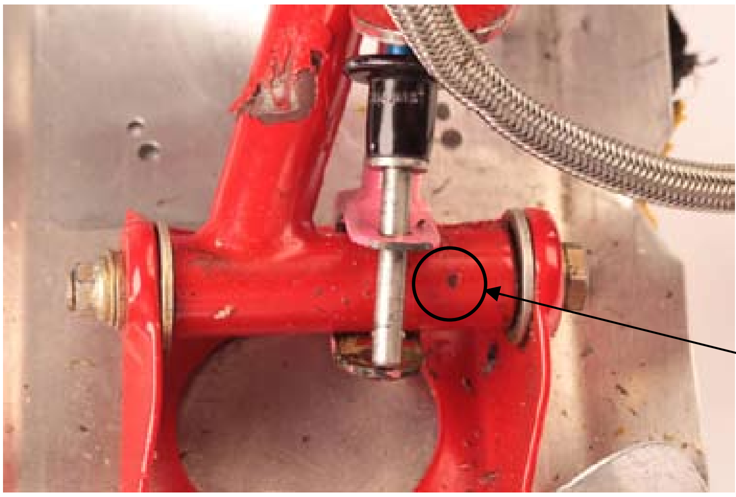
c) There was wear damage on both the left and right pivot tubes consistent with the lower attachment of the rudder extensions moving laterally.

d) There were witness marks on both pivot tubes. The evidence indicated that these were made by the pip-pins, which were positioned approximately 10 mm from the outboard vertical flange on the pedal base plate (Figure 7). These witness marks were probably made when the aircraft struck the ground, and might be indicative of the position of the lower attachments in the later stages of the flight.

e) Using a microscope, red traces were found on the tip of the pip-pin on the left pedal extension. However, there was insufficient material to carry out any detailed chemical analysis of the red traces.

f) There were several witness marks on the base plate of the left rudder pedal. These were approximately 10 mm from the outboard vertical flange on the pedal base plate (see Figures 8 and 9). The two most significant witness marks were made by an object approximately 2.5 mm in radius which is similar to the radius of the pip-pin. There was plastic deformation of the paint on both of these witness marks, consistent with the pip-pin gouging the paint as the rudder moved from a deflection to the left towards the neutral position.

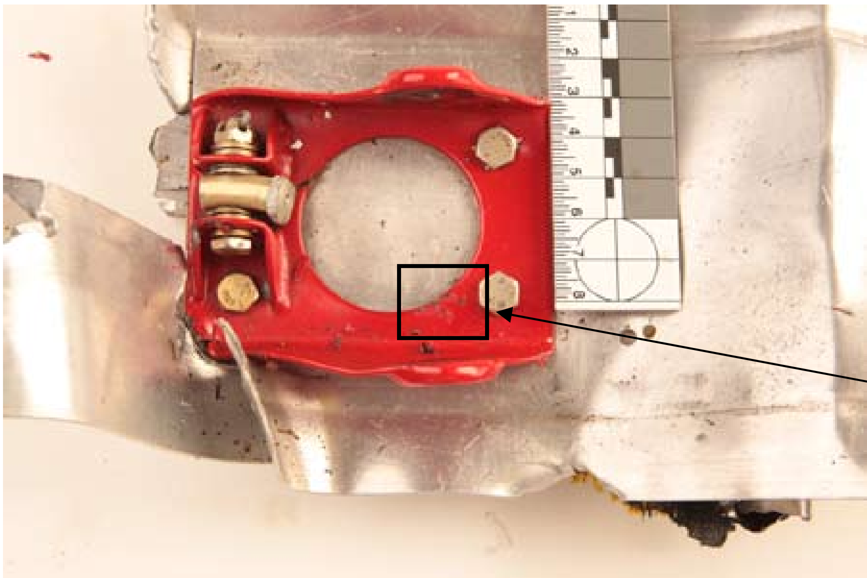
It was concluded that a rudder control restriction could occur if the lower attachment of the rudder pedal extension had moved outboard and the pedal in question, having been pushed forward, was subsequently moved



Note the witness mark on the pivot tube probably made by the pip-pin.

Figure 7

Front (and above) view of the left rudder pedal pivot tube
(Note that the lower attachment for the pedal extension, painted pink, can move relatively freely from left to right)



See close up in Figure 9

Figure 8

Base plate for left rudder pedal

Figure 9

Close up of Figure 8 showing witness marks probably made by the end of the pip-pin

aft towards the neutral position. The range of rudder positions in which a restriction could occur on the left pedal assembly, with the extension fitted, was estimated to be between 6° and 23° left rudder deflection. Similar values were estimated for a restriction on the right rudder assembly. It was concluded that, if such a restriction occurred, it was unlikely that the force a pilot could apply on the pedal extension would be sufficient to overcome the restriction. The way to free the pedals would be to shift the lower extension attachment point inboard.

Pilot information

The pilot was an American citizen and a former US aerobatic champion. She started flying small, high performance aerobatic aircraft soon after gaining a pilot's licence in 1993. She had owned an Edge 540 since about 1999 and was a highly experienced aerobatic pilot, having been a member of the US aerobatic team on three previous occasions.

Medical and pathological information

Postmortem examination

It was determined that the pilot died from multiple injuries consistent with being caused by the ground impact. Although the pilot was wearing a full harness and helmet, the forces involved were outside the range of human tolerance and were not survivable. There was no evidence of significant natural disease which could have caused or contributed either to death or the cause of the accident. Toxicological examination revealed no evidence of drugs or alcohol.

Physiological effects of high G forces

Competition aerobatics expose pilots to high G forces, the most hazardous of which is Gz: the acceleration acting from head to toe (+Gz) or from toe to head (-Gz). If the heart and vascular system cannot keep pace with the rapid onset of +Gz, pilot performance will be degraded and loss of consciousness will follow.[2]

Tolerance to +Gz has been the subject of many studies. Most show that G-induced loss of consciousness (G-LOC) occurs at around +4.5 Gz in an unprotected individual, although many factors can influence an individual's G tolerance. High accelerations can be tolerated for short periods of time, but will lead to loss of consciousness without warning (ie visual symptoms) if allowed to persist. Aerobatic pilots frequently take advantage of this, pulling very high +Gz loads but for only short periods of time.

An important aspect of G tolerance is the effect of rapidly changing from negative to positive Gz[3]. When a pilot is subject to –Gz there is a slowing of the heart, caused by a reflex reaction to increased blood pressure in the head and chest. Changing rapidly to +Gz would lead to a rapid speeding up of the heart as blood pressure in the head and chest dropped. However, the reflex system takes some time to respond to the change, so blood supply to the brain may decrease during the transition period, increasing the risk of G-LOC.

Recorded information

A portable radar tracking system was being used to allow judges to determine accurately when an aircraft strayed outside the competition box. The system, which included a slaved video camera, was located about 1,300 m to the north of the centre of the box. Video footage from the tracking system and a separate handheld camcorder were available for analysis.

Pull up for the accident manoeuvre started from 1,100[4] ft. The push over at the top of the manoeuvre started at 2,600 ft and the maximum height reached was 2,750 ft. The downwards snap roll was initiated at 2,300 ft. From that point, seven and a half turns were recorded before radar and optical contact was lost at an indicated 200 ft, when the aircraft disappeared from view behind trees. The observed height profile was

Footnote

2 Federal Aviation Administration (FAA) publication AM-400-09/4 '*Acceleration in Aviation: G-Force'*.

Footnote

3 FAA Advisory Circular 91-61 *'A hazard in aerobatics: effects of G-Forces on pilots'* (1984).

4 Heights are radar-derived, as indicated on the associated viewing software.

almost identical to the earlier practice manoeuvre. The handheld camcorder captured a further half turn before, again, the aircraft was lost from view behind trees, very shortly before it hit the ground. From initiation of the snap roll to the point of impact was 10.7 seconds.

Snap roll manoeuvre

Figure 10 shows comparative video images from the practice and accident manoeuvres, from a point just after initiation of the snap roll; the aircraft has rolled through about 120° at this point.

Figure 11 again shows images from the practice and accident manoeuvre, advanced nearly a full turn from the previous images, at about the point of recovery. Significant differences can be seen in terms of rudder angle and pilot's head position (the pilot was wearing a white helmet).

Figure 10

Shortly after initiation of the snap roll – the practice manoeuvre is on the left

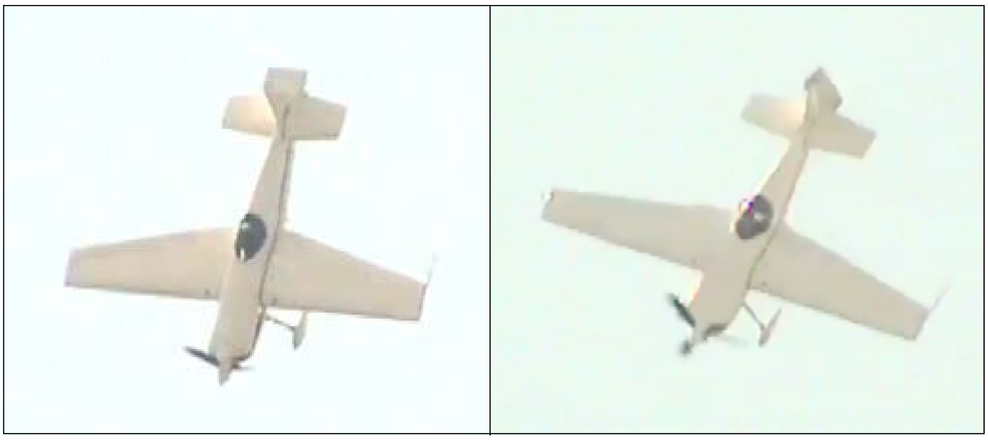


Figure 11

The point of recovery in practice manoeuvre (left) compared to the equivalent point during the accident manoeuvre

Control surface deflections

The radar-slaved video allowed a limited assessment of control surface positions. Figure 12 shows a graphical representation of rudder and aileron positions as the aircraft descended. The data begins at the point of intended recovery (1¼ turns after initiation of the snap roll) and ends when the aircraft descended out of view behind trees. Rudder position could only be accurately assessed when the aircraft presented a plan form to the camera, so the data points are plotted for every half turn. Increased data points are presented for aileron deflections; one per quarter turn. This was possible due to movement of the aileron spades under the wing, which allowed an assessment of their position when viewing the aircraft underside. Also, generally better views of aileron deflection allowed a degree of interpolation when the aircraft's upper plan form was presented to the camera.

Elevator position could not be measured with accuracy, but it was noted that, approaching the point of recovery from the snap roll, the aircraft's body pitch angle was 14° less nose-down than at the equivalent position in the practice manoeuvre (this is visible at Figure 11). For the first two turns after the expected recovery point, the elevator appeared approximately neutral, and the nose-down pitch angle increased to approximately 5° from vertical. During the next three turns there was noticeable 'up' elevator applied, and the nose-down pitch angle reduced to about 18° from vertical. The 'up' elevator remained applied until the aircraft disappeared from view a turn later.

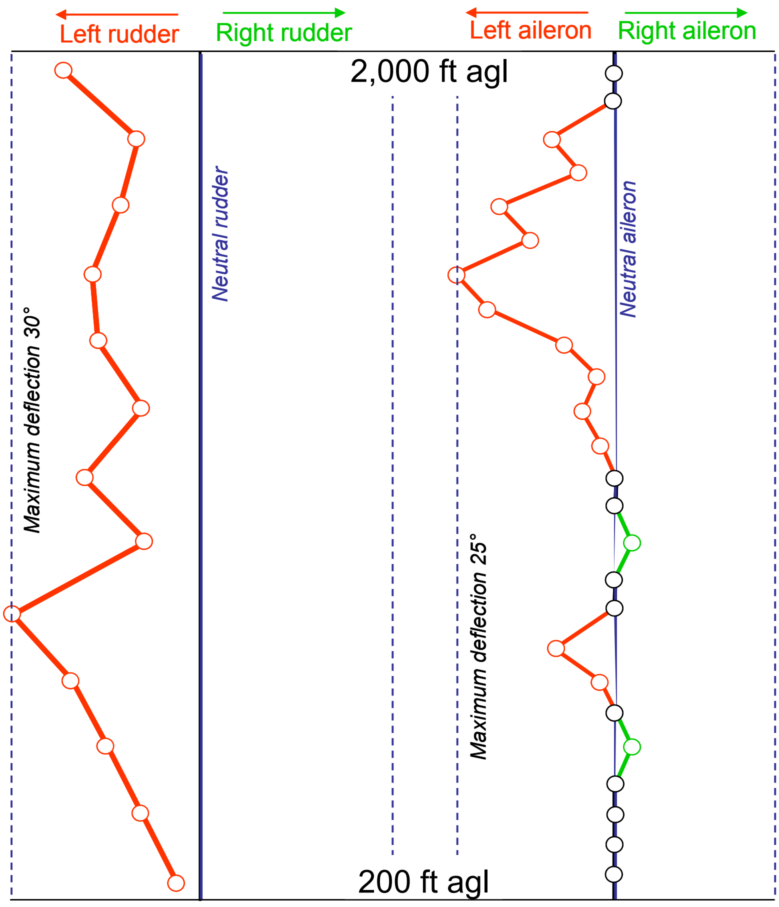


Figure 12

Rudder and aileron deflections

Control surface movement

Figure 13 shows two consecutive images taken during the accident sequence. They are separated by a fraction of a second, at a point about two turns advanced from the images in Figure 11. Despite the very short time interval, significant changes to rudder angle can be seen. The pilot's head position is also still considerably displaced to the left.

Pilot's head position

From the video images it can be seen that the pilot's head position during the early stages of the snap roll was approximately central in the cockpit, and was similar to the equivalent point in practice. However, at the point of expected recovery, the pilot's head is considerably left of centre. The video showed that the pilot's head remained to the left of the cockpit centreline until about half way through the descent, when it returned to approximately centreline and remained so until the video ceased.

Video analysis

The videos of the accident were shown to a number of experts in the field of aerobatics and competition flying, some of whom had also witnessed the accident. Their joint observations are summarised below:

a) At the point of recovery, although a brief application of rudder would have been expected to align the aircraft with the vertical, the observed rudder deflection is unusual.

b) The aircraft is not pitched as far forward on the accident recovery as on the practice, indicating insufficient forward movement of the control column during recovery.

c) The pilot's head would be expected to be central in the cockpit at the point of recovery, to allow the pilot to determine the correct recovery line.

d) Left applied rudder and aileron after the point of expected recovery is unusual: the rotation would have been driven by control deflection - most probably rudder rather than ailerons, as the rotation is not axial.

Figure 13

Two turns after the point of expected recovery, the two images are taken from the accident sequence and only a fraction of a second apart. Note change in rudder position

Previous incident

One of the pilots interviewed reported an incident which occurred while flying a similar snap roll manoeuvre in an Edge 540, in which he was temporarily unable to recover. During the aggressive application of left rudder required to initiate the manoeuvre, his foot came off the right rudder pedal. With the almost simultaneous application of positive 'g' his foot moved down and the heel of his shoe became caught in the aircraft tubular structure behind the metal footplates (see Figure 3). The pilot was unaware of this until he attempted to apply right rudder pedal to stop the rotation and realised that he could not.

It was only when the pilot looked down that he realised the nature of the problem, during which time the aircraft continued to rotate. He was able to correct the situation, but not before a number of unintentional rotations had occurred.

Analysis

Video analysis showed three anomalies at the expected point of recovery; the inappropriate rudder position, the unusual aircraft pitch attitude (compared to the practice case) and the pilot's head position, which would be expected to have been central in the cockpit at that point.

As the manoeuvre continued, there were no apparent control inputs made which could be regarded as being part of a positive recovery attempt. Instead, the rudder remained displaced in the direction of roll, driving the rotation. Although aileron deflection did return to near zero for much of the latter part of the descent, it was at times near full deflection in the early stages, again providing a strong driving force for the rotation. There was almost no aileron movement to oppose the rotation. The rudder position is the most significant anomaly. Either the pilot reacted correctly to the situation but was physically prevented from removing the pro-rotation rudder, or her ability to recognise and/or react to the situation had become impaired.

The examination of the rudder pedal assemblies revealed that a restriction could occur with this set of extensions fitted. Moreover, such was the design of the extensions that they could readily move outboard with normal operation (a requirement for a restriction to occur). This is corroborated by the wear marks on the outboard ends of the pivot tubes and the witness marks made by the pip-pins on the pivot tubes. Importantly, the witness marks on the base plate of the left rudder pedal were consistent with having been made by the pip-pin. This physical evidence suggested that a jam had occurred at some stage, with the left rudder pedal forward and moving towards neutral.

It was not possible to say when this may have occurred, but there was no report by the pilot of a rudder problem prior to the accident flight. It was not possible, either to say why the restriction, if it did occur on the accident flight, did not occur during the same and similar manoeuvres earlier in the flight.

Had rudder control been affected in such a way, it would account for the continued application of pro-rotation rudder, and perhaps also for the varying amounts and rate of rudder input as the pilot tried to free the unknown restriction. It could also account for a significant distraction during the recovery phase, leading to insufficient forward control column and hence the relatively high pitch attitude.

There was some evidence to suggest that the pilot may have experienced a problem similar to that experienced by another Edge 540 pilot in which his foot became trapped during a snap roll. The accident pilot was not using foot straps and it is known that she had recently had a problem when her right foot became significantly separated from the rudder pedal during a snap roll recovery. However, given that the other pilot quite quickly recognised and corrected the situation, and considering the accident pilot's extensive aerobatic experience, it would be expected that she would recognise and recover from such a situation before it became critical.

The pilot's head position to the left of cockpit centre was a further anomaly. If it was deliberate, it may have been an attempt to identify a problem with the pedals or her foot. At the point of expected recovery, she should have been looking centrally ahead to identify her roll out feature and ensure she achieved it accurately. As it would have taken a finite time to recognise that there was a problem inside the cockpit, she would not have been expected to look in straight away, yet her head position is well to the left at the point of expected recovery.

The final manoeuvre was not an extreme one for such an experienced aerobatic pilot, nor did it entail prolonged exposure to very high G forces. There was thus no direct evidence that the pilot had been affected by G-LOC. However, it would be expected that the pilot would have attempted all measures to resolve the situation, including vigorous and obvious control inputs to reduce angle of attack and oppose the rolling motion. No faults were identified with the aileron or elevator control systems, yet no such recovery inputs were apparent. The possibility therefore remains that the pilot's ability to recognise or respond to the situation had somehow become impaired, and this must be considered as a possible contributory factor.

Conclusion

The aircraft did not recover from a downwards snap roll. No recovery action was seen to be taken and the aircraft struck the ground after several rotations. Pro-rotation rudder was applied throughout and pro-rotation aileron applied for part of the descent. A mechanism was identified by which the pilot's rudder pedal extensions could have caused a restriction of the left pedal in such a way that left rudder could not be fully removed once it had been applied. The circumstances of the accident suggested that the pilot's ability to recognise or respond to the situation had somehow become impaired, and this must be considered as a possible contributory factor.