Factors Contributing to Accidents During Aerobatic Flight Operations

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INTRODUCTION: Aerobatic flight operations involve a higher level of risk than standard flight operations. Aerobatics imposes considerable stresses on both the aircraft and the pilot. The purpose of this study was to analyze civilian aerobatic aircraft accidents in Australia, with particular emphasis on the underlying accident causes and survival outcomes.

METHODS: The accident and incident database of the Australian Transport Safety Bureau was searched for all events involving aerobatic flight for the period 1980–2010.

RESULTS: A total of 51 accidents involving aircraft undertaking aerobatic operations were identified, with 71 aircraft occupants. Of the accidents, 27 (52.9%) were fatal, resulting in a total of 36 fatalities. There were 24 nonfatal accidents. In terms of injury outcomes, there were 4 serious and 9 minor injuries, and 22 accidents in which no injuries were recorded. Fatal accidents were mainly due to loss of control by the pilot (44.4%), in-flight structural failure of the airframe (25.9%), and terrain impact (25.9%). G-LOC was considered a possible cause in 11.1% of fatal accidents. Nonfatal accidents were mainly due to powerplant failure (41.7%) and noncatastrophic airframe damage (25%). Accidents involving aerobatic maneuvering have a significantly increased risk of a fatal outcome (odds ratio 26).

DISCUSSION: The results of this study highlight the risks involved in aerobatic flight. Exceeding the operational limits of the maneuver and the design limits of the aircraft are major factors contributing to a fatal aerobatic aircraft accident. Improved awareness of G physiology and better operational decision-making while undertaking aerobatic flight may help prevent further accidents.

KEYWORDS: aerobatic flight, injury, fatality, accident, G force, risk.

Newman DG. *Factors contributing to accidents during aerobatic flight operations*. Aerosp Med Hum Perform. 2021; 92(8):612–618.

Aerobatic flight operations involve a higher level of risk than standard flight operations. What separates aerobatic aircraft from nonaerobatic aircraft is their much wider performance envelope, particularly their ability to generate high $+G_z$ loads during maneuvering. These high levels of $+G_z$ impose considerable stresses on both the aircraft and the pilot.[4,10,11]

The G environment of aerobatic aircraft has been examined by several authors.[1,2] In one study, the G environment of the Extra 300 (a high performance aerobatic aircraft manufactured by Extra Flugzeugbau in Germany) was found to range from $+8\ G_z$ to $-6\ G_z$.[2] Very high performance civilian aerobatic aircraft can generate extremely high peak $+G_z$ levels (to $+10\ G_z$ and beyond), with significant exposure to the $-G_z$ component of the maneuvering envelope and with high roll rates.[10] While the agility of these aircraft is high, elevated $+G_z$ loads cannot be sustained for long periods. Their maneuvering is thus typically described as abrupt and occasionally violent.[1] It has been shown that the time to make the transition from $+5\ G_z$ to $-5\ G_z$ can be very brief, on the order of 3 s or less, in these very agile aerobatic aircraft.[4] The performance envelope of civilian aerobatic aircraft thus contrasts with that of military fast jet aircraft, which tend to generate less peak $+G_z$, but are able to sustain this $+G_z$ level for longer periods.[11]

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This manuscript was received for review in October 2020. It was accepted for publication in May 2021.

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DOI: https://doi.org/10.3357/AMHP.5810.2021

The obvious risk to a pilot performing such maneuvers is G-induced loss of consciousness (G-LOC). Where the level of applied $+G_z$ impairs the ability of the cardiovascular system to maintain adequate cerebral perfusion, loss of consciousness results.[10] The subsequent risk to the aircraft and its occupants, particularly where the maneuver is conducted at a low altitude, is considerable.

In the military aviation domain, decades of experience have led to a good understanding of the nature of the high $+G_z$ environment, as well as the myriad physiological effects of exposure to high $+G_z$ loads and the various countermeasures that can be deployed to mitigate these adverse effects.[9,10] There is also anecdotal and scientific evidence that repetitive exposure to the high $+G_z$ environment confers a degree of protective cardiovascular adaptation on pilots of high performance aircraft.[12,13] However, despite decades of practical experience with $+G_z$ loads and the significant amount of research that has been conducted, there remain ongoing challenges with protecting pilots from the adverse effects of $+G_z$ exposure, as well as gaps in our understanding of the physiological effects (such as the duration of the adaptation benefit, and the optimum method for preventing $+G_z$-induced neck injuries, among others). This situation is even more pronounced in the civilian aerobatic environment, which has not received the same amount of research attention as military fast jet operations.

There have been multiple studies over the years examining the prevalence of G-LOC in military operations. In general, the observed rate tends to be in the range of 8–19%.[6,16,18] In a study of Royal Australian Air Force F/A-18 and Hawk 127 pilots, a G-LOC rate of 9% was found.[15] In a recent UK study, 14.8% of Royal Air Force (RAF) pilots surveyed had experienced a G-LOC event during their flying career.[17] A U.S. Air Force study found a G-LOC rate of 25.9 per million flight sorties between 1982 and 2002.[8]

While G-LOC is an obvious risk to civilian aerobatic pilots, the actual prevalence of G-LOC in civilian aerobatic flight operations is largely unknown. A 1982 study documented four cases of possible G-related civilian aerobatic accidents, with two of these being fatal.[7] In the two nonfatal accidents, both were attributed to G-LOC based on the individual pilot reports. The authors noted that due to inadequate reporting and investigating, the true prevalence of G-LOC in civilian aerobatic operations remains unknown.

There are very few reports in the aeromedical literature that have examined aerobatic aircraft accident outcomes. In a study involving 494 aerobatic aircraft accidents in the United States, a fatality rate of 80.8% was found.[5] Failure to maintain altitude and therefore subsequent impact with the ground was identified as the main cause of a fatal outcome. The pilots in that study were generally very experienced, with half having over 7500 h of flight time. The authors noted the apparent preponderance of homebuilt aircraft in these fatal accidents, with engine and structural failures contributing to the accident. They recommended that homebuilt aircraft be subjected to greater regulatory oversight.

A New Zealand case-control study which examined all civil aircraft accidents during the period 1988–1994 found that aerobatic flight was associated with the greatest likelihood of fatality (OR = 46.88) and serious injury (OR = 13.3) in an accident.[14] This study focused on risk factors for injury in all civil aircraft accidents, with aerobatic accidents as a subcategory. The recommendations made by the authors were related to general accident factors, such as measures to reduce postcrash fire risk, better location identification, and improvements to onboard survival and first-aid equipment.

The purpose of this study was to analyze accidents involving civilian aerobatic flight operations in Australia. The main emphasis of the analysis was to examine aerobatic operations, with a focus on the underlying accident causes, survival outcomes, and flying hours of the pilots involved, and by so doing to determine the main factors contributing to accidents during aerobatic flight operations. This allows safety recommendations for improving aerobatic flight safety to be made and issues requiring further research to be identified. Understanding the factors that can contribute to such accidents is an important step toward improving the safety of aerobatic flight operations.

METHODS

The accident and incident database of the Australian Transport Safety Bureau (the ATSB) was comprehensively searched for all accident events in which the type of flight operation was identified as "aerobatic flight." The period chosen was a 30-yr period, from 1980–2010. This period was chosen in order to give a sufficient breadth of accident and incident data, and to ensure that all accidents that occurred within that period were captured in the database (since some complex accidents can take a significant period of time for the final report to be published).

In accordance with the Transport Safety Investigation Act 2003, the ATSB database records events according to occurrence type: accidents, incidents, and serious incidents. The ATSB definition of an accident is "an investigable matter involving a transport vehicle where: (a) a person dies or suffers serious injury as a result of an occurrence associated with the operation of the vehicle; or (b) the vehicle is destroyed or seriously damaged as a result of an occurrence associated with the operation of the vehicle; or (c) any property is destroyed or seriously damaged as a result of an occurrence associated with the operation of the vehicle."

A serious incident is an occurrence involving circumstances indicating that an accident nearly occurred. According to ICAO, the difference between an accident and a serious incident is essentially in terms of the end result. An incident is defined as all other investigable and reportable matters where safety was potentially affected.

For each event, the following parameters were recorded: occurrence date, location, whether a formal ATSB investigation was conducted, occurrence type, aircraft highest injury level, total people on board, total fatalities, total serious injuries, total minor injuries, total nil injuries, aircraft type, manufacturer and model, operation type and operational parameters (altitude, etc), and the underlying cause of the occurrence.

As an additional analysis, the accidents were grouped according to whether the accident was a result of aerobatic maneuvering or due to nonmaneuvering causes (e.g., engine failure). The aim of this analysis was to determine whether there was a greater number of fatal accidents during actual maneuvering flight than during nonmaneuvering flight. Fisher's Exact Test was the statistical test of choice, and an alpha level of $P < 0.05$ was considered significant. To further analyze the survival outcomes of aerobatic operations, an odds ratio (OR)[3] was calculated for fatal outcome, maneuvering-related accidents vs. accidents occurring as a result of nonmanoeuvring causes. The OR gives an indication of the association between an exposure and an outcome. In this case, the OR gives the odds that a fatal outcome will occur during aerobatic maneuvering compared with the odds of a fatal outcome occurring in the absence of that exposure, i.e., during nonmaneuvering flight. Similarly, relative risk (RR) was calculated to examine the probability of a fatal outcome occurring in maneuvering-related accidents.

RESULTS

The ATSB database for the search period 1 January 1980 to 31 December 2010 comprised an all-cause, all-classification total of 1234 accidents, 806 serious incidents, and 35,003 incidents, giving an overall occurrence total for the study period of 37,043 events. Of this total, 294 events were formally investigated by the ATSB. The ATSB does not investigate every occurrence—it deploys its resources selectively and gives priority to accidents and serious incidents that may represent a significant threat to fare-paying passengers and public safety.

Of the 1234 accidents, 135 were fatal (10.94%). The reported injuries were serious in 104 cases (8.43%), minor in 299 cases (24.23%), and nil in 0 cases. For the study period, a total of 51 accidents involving aircraft undertaking aerobatic flight operations were identified. This represents only 4.13% of all the accidents and only 0.14% of all the occurrences recorded on the ATSB database for the 30-yr study period. In these aerobatic accidents, 71 aircraft occupants were involved.

The aircraft types involved in these 51 aerobatic accidents represent a cross-section of aerobatic-capable aircraft, from relatively low performance historic biplanes (such as the De Havilland DH-82 Tiger Moth) to the high-performance end of the operational spectrum (such as the Extra 300S and the Pitts S-2A). There was a total of 33 different aircraft types involved in these 51 accidents. The most common aircraft type involved was the Pitts Special variant (11 accidents), with the two next most common aircraft types being the Bellanca 8-KCAB Decathlon (3 accidents) and the De Havilland DH-82 Tiger Moth (3 accidents). All other aircraft types were represented in two or less accidents. From a performance perspective, 13 accidents were attributed to high-performance aerobatic aircraft (such as the Pitts variants and the Extra 300) and 38 accidents were attributed to low-performance aircraft types.

Accounting for the majority of accidents, 34 accidents (67%) occurred during aerobatic practice flights. There were nine accidents which occurred during aerobatic displays, three during passenger flight experience operations, three during aerobatic training, and two during test flying operations. In terms of pilot experience, the average total flight time was 2886.8 h (range 210–15,500) and the average time on type was 137.7 h (range 2–650).

The various causes of the accidents are shown in **Fig. 1**. The most common cause of the accident was loss of control in 15 cases (29.41%), with failure of the structural integrity of the aircraft the second most common (25.49%).

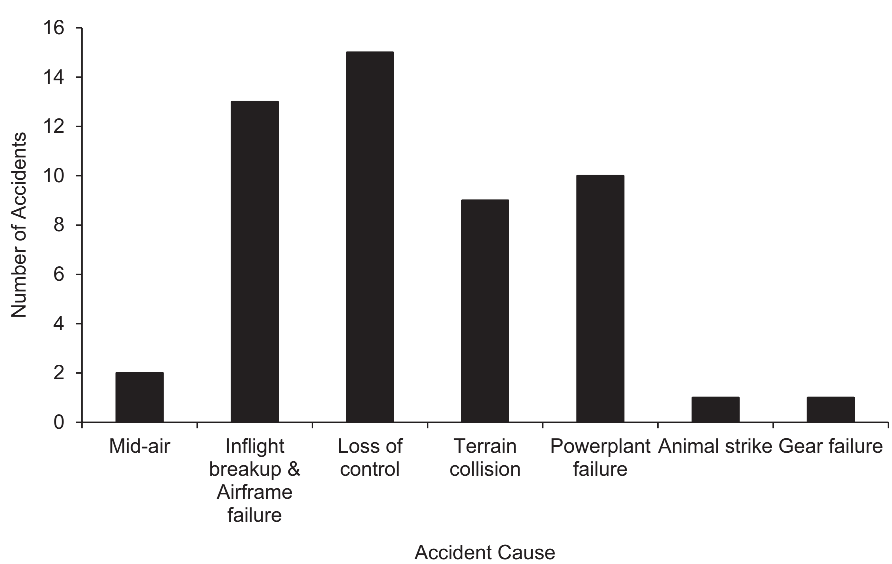

Fig. 1. Accident causes.

In an example of a loss of control event, the accident pilot was practicing low level aerobatics in a prototype aircraft. Witnesses saw the aircraft enter a vertical climb from about 500 ft. It then entered a brief tail slide before descending in a steep spiral roll or spin to the left. The aircraft struck the ground in a steep nose low attitude, apparently as recovery from the spin or spiral was initiated. The pilot had previously obtained an aerobatic endorsement, but had not been cleared to perform low level aerobatics.

In an example of failure of structural integrity, a DH-82 Tiger Moth aircraft with two people on board was observed by witnesses performing a loop in the training area. During the recovery from this looping maneuver, the wings disintegrated and the aircraft impacted the ground in a near vertical attitude and caught fire. Both occupants were fatally injured.

In terms of the survival and injury outcomes of the accidents, 27 accidents (52.9%) were fatal, resulting in a total of 36 fatalities. There were 24 nonfatal accidents. There were four accidents in which serious injuries were sustained, and nine accidents in which minor injuries were sustained. In 22 accidents no injuries were recorded. In terms of type of flight operation, 19 of the 27 fatal accidents occurred during aerobatic practice, and 5 during aerobatic displays. Two fatal accidents occurred during passenger experience flights, and one during an aerobatic instructional flight. For the accidents with fatal outcomes, the average total flight time of the pilots was 2543.1 h (range 279–15,500) and the average time on type was 101.0 h (range 2–400). For the accidents with nonfatal outcomes, the average total flight time of the pilots was 3803.3 h (range 210–6500) and the average time on type was 260.0 h (range 30–650).

Fig. 2 shows the causes of accidents that resulted in fatalities. The most common causes of an accident resulting in a fatal outcome were loss of control by the pilot (44.4% of cases), in-flight structural failure of the airframe (25.9% of cases), and terrain impact (25.9% of cases). There was one case involving a fatal midair collision during a formation aerobatic display. In three accidents (11.1%), G-LOC was considered as a possible cause of the accident. The accident investigations were not able to positively identify this as a cause, with the result that in the official reports of these three accidents, the cause was attributed to terrain impact in two cases and loss of control in the other.

As an example of a fatal loss of control accident that may have been G-related, a Bellanca 8-KCAB Decathlon aircraft with a single pilot onboard carried out several aerobatic maneuvers. Witnesses noted that the entries to some of these maneuvers were performed at higher G loadings than normal. The aircraft was seen to then enter a spiral dive, with no apparent recovery effort. The aircraft impacted the ground and was destroyed by fire. The pilot was killed. No defect or malfunction was found with the aircraft or its systems. The pilot was current for aerobatic flight. There was no evidence of any physical illness or incapacity of the pilot. It was evident that the aircraft was not under control during the spiral dive. G-LOC was considered as a possible cause.

Fig. 3 shows the causes of those accidents in which the outcome was nonfatal. The most common cause of such survivable accidents was powerplant failure, in 41.7% of cases. An example of this occurred to a Pitts S-1 aircraft, with one occupant. During aerobatic practice, the aircraft suffered an engine failure at 1000 ft (304.8 m). A forced landing was conducted successfully, with no injuries to the pilot.

Noncatastrophic airframe damage was the second most common cause of such accidents in 25% of cases. As an example of this, an American Eagle II aircraft with one pilot on board was carrying out a series of aerobatic maneuvers when the propeller separated from the airframe. A forced landing was carried out in a suitable paddock. The pilot then noted that one wing had sustained damage from the departing propeller. The evidence indicated that the propeller fell from the aircraft when the remaining five of the six propeller retaining bolts failed as a result of fatigue cracking and overload. The sixth bolt was not found—evidence indicated that it had fallen out prior to failure of the other five bolts. The investigation noted that wood

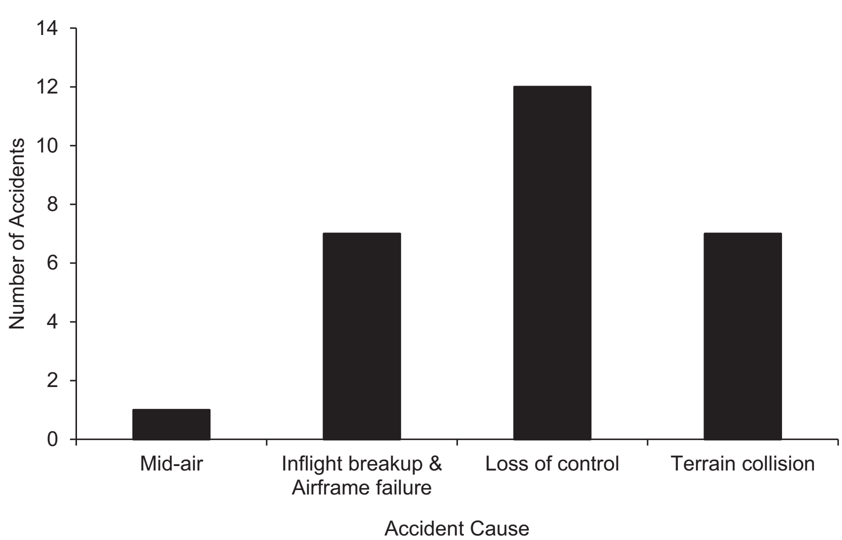

Fig. 2. Fatal outcomes by accident cause.

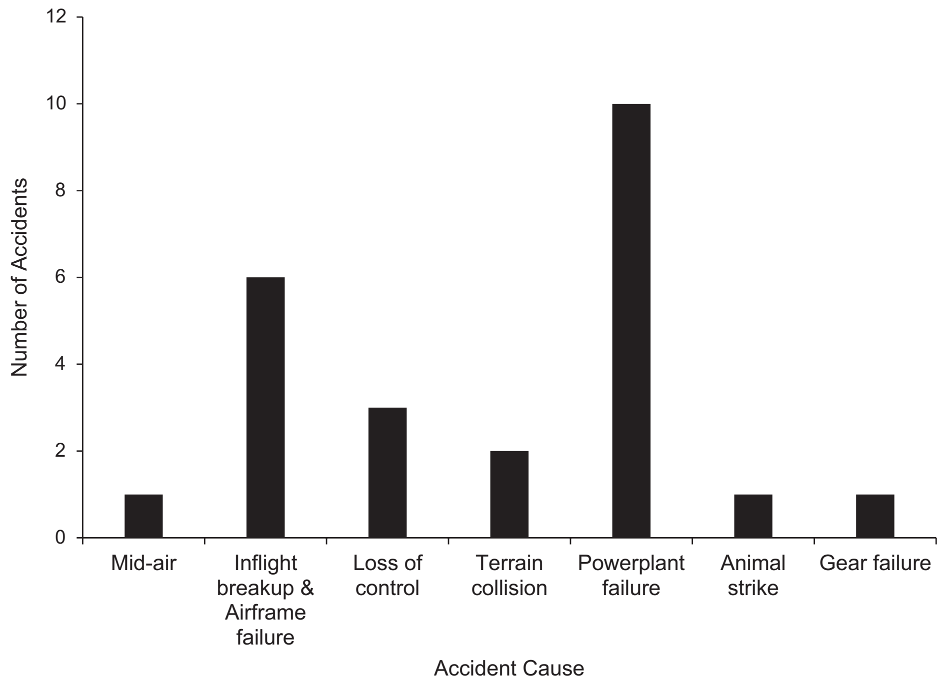

Fig. 3. Nonfatal outcomes by accident cause.

shrinkage of the propeller and associated loosening of the retaining bolts was a known problem and the subject of an Airworthiness Directive. The recommended maintenance procedures had not been adequately carried out.

Survival outcomes in accidents involving aerobatic maneuvering were compared with survival outcomes for accidents involving nonmaneuvering flight. Of the accidents involving aerobatic maneuvering, 68.4% resulted in fatalities compared with only 7.7% of accidents involving nonmaneuvering flight. Statistical comparison of these accident outcomes showed that accidents involving aerobatic maneuvering have a significantly greater fatality rate compared with accidents in which aerobatic maneuvering was not occurring ($P < 0.0001$, Fisher's Exact Test). These data were used to calculate the OR for a fatal outcome from an aerobatic maneuvering event. The calculated OR was 26. This shows that the odds of being fatally injured are significantly higher in an accident involving aerobatic maneuvering than in an accident in which aerobatic maneuvering was not occurring.

The RR of a fatal outcome from an accident involving aerobatic maneuvering was also calculated using the fatality rates calculated above. The RR was 8.9, which shows that, based on this data set, for an accident involving aerobatic maneuvering, the risk of being fatally injured is 8.9 times greater than an accident in which aerobatic maneuvering was not occurring.

DISCUSSION

The results of this study illustrate the increased risks associated with aerobatic flight. In 38 of the 51 accidents examined, the aircraft was conducting aerobatic maneuvers at the time of the accident. The fatality rate in these accidents was significantly different from that seen in accidents where aerobatic maneuvering was not being performed. The calculated odds ratio of 26 and the relative risk of 8.9 both show that the odds of being fatally injured are significantly higher in an accident involving aerobatic maneuvering than in an accident in which aerobatic maneuvering was not occurring.

As noted in the introduction, there is a paucity of published aeromedical literature on civilian aerobatic accident outcomes. Those studies that have been published adopted different methodological approaches to their analyses. However, despite these different approaches, their overall findings are consistent with those of the present study, in that they demonstrate that aerobatic operations have a higher inherent level of risk than nonaerobatic operations.[5,14]

In the present study, 3 of the 27 fatal accidents (11.1%) listed G-LOC as a possible contributing factor. Significantly, the vast majority of fatal accidents occurred during either aerobatic practice or aerobatic display (88.9%). Of the fatal accidents, 44.4% were attributed to loss of control, which was the greatest contributor to the fatal accidents. An unknown number of these accidents may be due to G-LOC. Of fatal accidents in the present study, 25.9% were attributed to terrain impact, which may also have included a subset of G-LOC events. This cannot be known with any certainty based on the data available. It is difficult to establish beyond doubt whether a fatal accident involving a civilian aerobatic aircraft was ultimately a result of G-LOC leading to loss of control by the pilot and subsequent terrain impact. As such, it is reasonable to assume that the true incidence of G-LOC in aerobatic accidents is under-reported. Given this, and the fact that pilot incapacitation due to G-LOC is a recognized threat in aerobatic flight operations,[5] it should therefore always be considered a possibility when investigating aerobatic aircraft accidents.

This study showed that exceeding the operational limits of an aerobatic maneuver can lead to an accident. While the effects of $+G_z$ discussed above reflect a physiological issue, exceeding the operational limits of a maneuver tends to be a human factors issue. The reasons for such an exceedance by a pilot are many and varied. They include poor decision-making, poor or inadequate estimations of height or airspeed, and failure to properly fly the intended maneuver. Such behavior may reflect a problem with preflight planning, supervision, training, or a more generalized poor approach to risk assessment. In the present study, there were several accidents in which the aircraft had insufficient altitude to recover from a particular maneuver. In a small number of cases in the present study, the aerobatic sequence was flown by pilots not certified for aerobatic flight. Perhaps not surprisingly, these typically resulted in a loss of control and subsequent fatal ground impact.

Where the maneuver is flown incorrectly, at the wrong altitude or airspeed, the aircraft can be placed at risk. Insufficient altitude to recover from an aerobatic maneuver, with no escape maneuver planned, can lead to impact with terrain. Flying the maneuver at too low an airspeed (on entry to the maneuver) can lead to the aircraft losing too much energy during the maneuver, resulting in a departure from controlled flight, for example, as a result of bleeding off too much airspeed. Inadvertent or deliberate mishandling of the energy state of the aircraft is thus a significant risk to the safe operation of an aerobatic aircraft.

It is useful here to examine the results of the analysis relating to pilot flying experience and time on type. Pilots involved in fatal accidents had much less time on type than those involved in nonfatal accidents. In one case, the accident pilot had over 15,000 h of total flight time, but only 2 h on type, and was involved in a fatal aerobatic accident. In a previous study, nearly half of the pilots involved in aerobatic accidents had over 7500 total flight hours, but time on type was not reported.[5] In another study examining accidents in civil aircraft including aerobatic operations, total flight experience was not found to be a risk factor for fatality or serious injury.[14] Total flight time thus appears to be less important than time on type in terms of aerobatic flight outcomes. Domain experience in the more dynamic aerobatic environment rather than total overall flight experience appears to be more important as a factor determining accident outcomes.

Another factor identified in this study as contributing to civilian aerobatic accidents was exceeding the design limits of the aircraft itself. This typically reflects a maneuver that is beyond the maximum stress and force tolerances of the aircraft such that damage occurs. This can be due to pulling too much G at a given weight and/or airspeed. Such damage may then lead to a crash landing or, more typically, failure of the structural integrity of the aircraft and a dramatic reduction in its ability to remain airborne or controllable. The aircraft then enters an out-of-control state, which is then often associated with a fatal outcome. Separation of a wing or a critical control surface was seen in a number of cases in the present study. This factor also raises the issues of airworthiness and maintenance, especially in older aircraft and homebuilt aircraft, a factor identified in other reports.[5] A well-trained, competent, and current pilot in an unairworthy aircraft still represents a flight safety risk.

It is worth noting that in the present study fatal outcomes were all associated with operational issues rather than aircraft mechanical issues or landing issues. These latter issues were not associated with a loss of aircraft control. This reinforces the fact that loss of control in an aerobatic aircraft is more likely to lead to a fatal outcome. In military fast jet operations, the use of an ejection seat affords the aircrew a way to safely leave an aircraft that has departed controlled flight. This is not an option available to pilots of civilian aerobatic aircraft. Some aerobatic pilots wear parachutes during flight, but the safe deployment of a parachute is predicated on the ability of the pilot to manually extricate themselves from the out-of-control aircraft. This may not be possible, depending on the dynamic state of the aircraft and the G loads imposed. It is thus interesting to note that in one of the cases in the present study the pilot was able to safely egress from an aircraft in an unrecoverable spin and parachute to the ground.

A number of recommendations can be made on the basis of the findings of this study. Firstly, there are some areas of training that could potentially be improved. Such training could include improved aeronautical decision-making and risk management for aerobatic pilots, especially those with significant flight experience but little aerobatic experience, incorporating greater awareness of pilot-based factors that increase operational risk, e.g., G awareness training. Improvements to competency-based training of aerobatic pilots could be made in terms of reinforcing the operational limits of planned maneuvers and the aircraft's inherent limits. In addition, better supervision of newly qualified aerobatic pilots might also offer some operational protection.

Secondly, improved data coding for aerobatic aircraft accident investigations would be beneficial. A consistent approach to coding accident causation over time would help and, where G-LOC is a possible cause, it would be helpful if this was mentioned in the accident report narrative. It would also be useful if pilots were encouraged to report issues that did not lead to an accident, such as a G-LOC event from which the pilot recovers and safely lands the aircraft. That data would be extremely helpful in driving a better understanding of the true prevalence of G-related problems in civilian aerobatic operations.

Thirdly, more research is clearly needed. Studies directly examining the prevalence of G-related issues in civilian aerobatic pilots should be conducted, along similar lines to the well-documented studies in military pilots discussed previously. The results of such studies would potentially give a more accurate indication of G-LOC prevalence in civilian aerobatic operations and the conditions under which it occurs. Studies examining the G environment of different classes of aerobatic aircraft would also be beneficial. Studies such as these, along with enhanced reporting of accidents and incidents, would give a more accurate picture of G-related events in civilian aerobatic operations.

Finally, it is worth considering what technological solutions might help mitigate the risks of aerobatic flight operations. Time-stamped G data acquired via an internal, aircraft-mounted flight data recorder would be helpful to accident investigators. This data would give investigators a clear idea of the maneuvering environment of the aircraft at the time of the accident. The flight data recorder would not need to be the same as that mounted in commercial passenger aircraft. It could be a much simpler device that sampled only certain channels of flight data (but should include G loads). Additionally, a cockpit-mounted camera that recorded the pilot's face would also be helpful, as it could show whether a pilot was conscious or not at the time of the accident. Clearly there are issues that would need to be resolved in the integration of these devices, especially in terms of cost, data privacy, and implications for airworthiness of the aircraft. A full cost-benefit analysis would need to be done. Suffice to say, however, that if a recording of a pilot's face was available along with time-stamped G data, then the process of attributing cause as part of an accident investigation would be made fundamentally easier.

In conclusion, the results of this study highlight the risks involved in civilian aerobatic flight operations. Exceeding the operational limits of the maneuver and the design limits of the aircraft are major factors contributing to a fatal aerobatic aircraft accident. Furthermore, accidents involving aerobatic maneuvering have a significantly increased risk of a fatal outcome. More research is needed into the nature of these operations to more fully understand the environment and to improve safety outcomes. Improved awareness of G physiology and better operational decision-making while undertaking aerobatic flight may help prevent further fatal accidents.

ACKNOWLEDGMENTS

Financial Disclosure Statement: The authors have no competing interests to declare.

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