General Aviation Joint Steering Committee

Safety Enhancement (SE) 41 – Survivability

Final Report

October 2017

Introduction

Crashworthiness in general aviation aircraft is a topic that requires substantial consideration, yet due to overly prescriptive regulatory requirements over the past several decades, has not advanced to the same level as other modes of transportation. The recent reorganization of the small airplane airworthiness rules (14 CFR part 23) and the use of globally accepted consensus standards as a means of compliance (ASTM, EUROCAE, SAE, RTCA, etc.) allows for greater innovation and flexibility in the way survivability and crashworthiness are approached. It is because of these recent developments that there is now an opportunity to reexamine crashworthiness standards for general aviation aircraft.

Utilizing processes established by the Commercial Aviation Safety Team (CAST) and the General Aviation Joint Steering Committee (GAJSC), a working group was established by the GAJSC to examine crashworthiness and survivability factors[1]. Specifically, this recommendation stemmed from the third working group under the GAJSC, which examined accidents caused by System Component Failure – Powerplant (SCF-PP). Not only were crashworthiness issues ranked highly as an effective safety enhancement, but figure 1 highlights why crashworthiness is such an important issue to address when examining fatalities caused by engine failures.

This white paper will outline the work and process of the survivability and crashworthiness group, highlight findings and propose several recommendations to ASTM.

[1] The General Aviation Joint Steering Committee (GAJSC), a joint government/industry group, was formed in the mid-1990s to reduce GA accidents. Revitalized in 2011, the GAJSC uses the same approach as the Commercial Aviation Safety Team (CAST (a data-driven, consensus-based approach) to analyze safety data to develop specific interventions to mitigate the root causes of accidents involving general aviation (GA) aircraft.

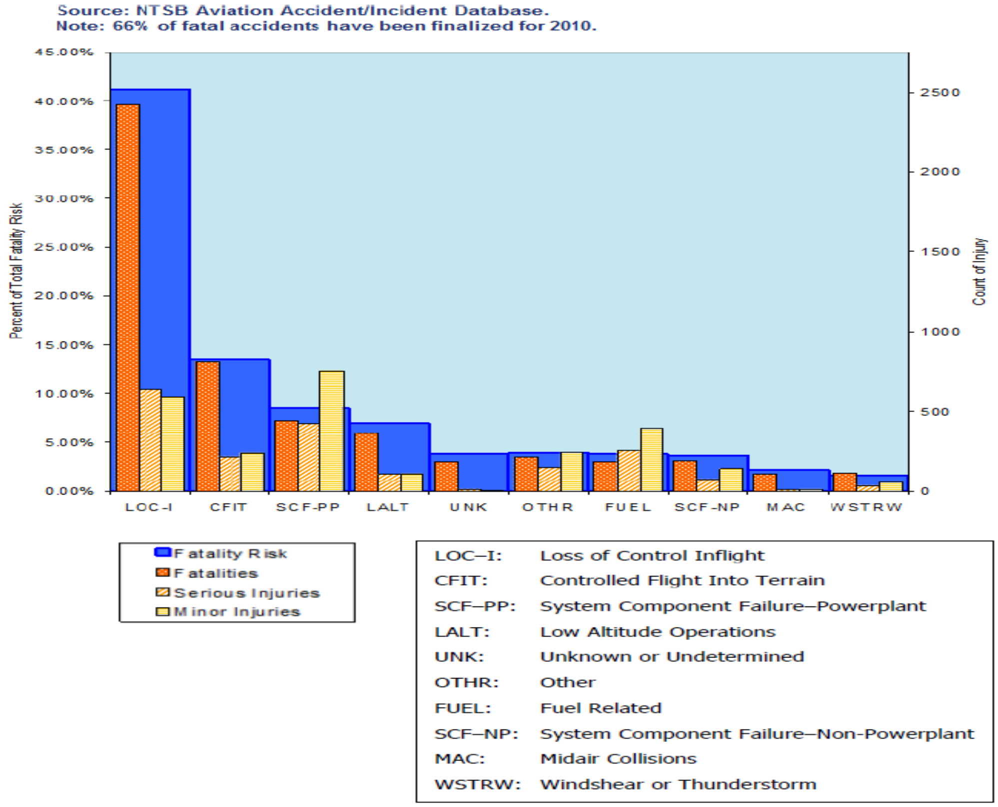

Figure 1. 2001-2010 GAJSC Accident Data Fatality Risk Analysis, Top 10

Executive Summary

The recommendation of the GAJSC was to establish a working group aimed at addressing survivability factors and crashworthiness in general aviation aircraft. Subject matter experts from ASTM, Civil Aerospace Medical Institute (CAMI), EIT Avionics, Embry-Riddle Aeronautical University, Engineering Systems Inc. (ESI), Federal Aviation Administration (FAA), General Aviation Manufacturers Association (GAMA), National Aeronautics and Space Administration (NASA), National Institute of Aviation Research (NIAR), National Transportation Safety Board (NTSB), Terrafugia, and Textron Aviation were all invited to participate.

Initially it was believed that a meta-analysis of existing work in the field would be enough to make meaningful recommendations to ASTM. However, after the working group's initial meeting, it was determined that additional examination of accidents would be required. Through specific CAST/GAJSC processes, analysis was conducted on twenty accidents that were deemed fatal but survivable[2].

From that analysis, there were recurring themes which indicated that addressing the following four key areas would result in significant improvements in crashworthiness (in order of priority):

- occupant restraints,
- survivable volume,
- impact energy management, and
- post-crash fire.

Methodology

Each member of the working group was assigned two to three accidents from the previously determined database, from which basic event data points were extracted from the accident sequence. Accidents that were analyzed included some fatal injuries and some survivors to get a better understanding of the performance limits of the current state of crashworthiness. In order to do this the NTSB final report and information contained in the docket were examined. Initially the group determined the approximate energy level, high or low, and the primary impact angle, vertical or horizontal. From there, they examined the problem (what went wrong) with emphasis on crashworthiness. For example, the working group members might have noted that the shoulder harness did not hold, or that the seat did not remain bolted to the floor.

With one phone call and one in-person meeting, the working group then further examined each of the twenty accidents spending time to carefully examine the data available, including; photographs, wreckage diagrams, and autopsy reports when available. Information available was often limited to what is publicly available in the NTSB's docket. After analysis and identification of problem statements, the group determined intervention strategies that could be turned into safety enhancing recommendations.

Summary of Data – Key Findings

In medium to low energy crashes, multiple trends in the data began to emerge after the first few accidents. It became clear that restraining the occupants and maintaining the survivable volume was key to increasing the odds of survivability of the occupant.

Blunt force trauma, often accompanied by post-crash fire, are the largest causes of fatalities identified in this study. Obviously, rapid deceleration greatly reduces the possibility of survivability but this issue isn't simply related to crash velocity, there exist possibilities to aid the airplane in dissipating crash energy.

The additional data presented in this paper reflects basic data points that were found throughout the review. The accidents were classified into general categories that identified the relative severity of the crash (energy level, velocity vector) and safety-system performance (restraints, post-crash fire) based on the limited information available. Because information was limited at

[2] The working group identified these accidents as those where at least one person on board survived the accident, but – in some cases – other persons onboard the accident aircraft did not survive.

times, all accidents could not be identified as one classification or another, so not all twenty accidents will be represented in certain categories.

Low Crash Energy	High Crash Energy	Horizontal Crash Velocity	Vertical Crash Velocity
11 accidents	**8 accidents**	**10 accidents**	**8 accidents**

Table 1. Crash Energy and Velocity

	Seatbelts or Harnesses Used	Restraints Held
Yes	**11 accidents**	**7 accidents**
No	**3 accidents**	**5 accidents**

Table 2. Occupant Restraints

	Post-Crash Fire
Yes	**10 accidents**
No	**10 accidents**

Table 3. Post-Crash Fire

Recommendations Summary

The GAJSC working group has developed four categories of recommendations that would contribute to increased aircraft crashworthiness and occupant survivability. These recommendations, in order of importance, will be split into both forward fit and retrofit and further elaborated upon.

1. Pilot and Occupant Restraints

   While occupant protection can be achieved by both ensuring survivable volume and reducing impact energy, effective restraints must be in place to take advantage of these improvements. Effective restraints are often the more cost-affordable solution for reducing fatalities and injuries, especially in the retrofit market. Lateral forces applied to the head and neck were noted to be injurious or fatal in several of the accidents examined. There are multiple restraint solutions that can lead to increased survivability;

torso restraint, inflatables, pre-tensioners, load limiters, and more robust restraints overall. While dynamic restraints performed well in this role, there is potential to properly restrain occupants with systems that utilize static load testing to adequate levels. This technique, partnered with structure that might maintain survivable volume, has a great potential to save lives.

2. Maintain Survivable Volume

   The overwhelming majority of the accidents reviewed resulted in fatalities due to the survivable volume being either reduced or penetrated. Ensuring the integrity of survivable volume of the occupied areas (i.e. cockpit and cabin) in the aircraft is crucial to prevent fatalities. Additionally, survivable volume integrity is necessary for occupant egress post-crash. Designs, which might include adequate occupant restraint (even if not dynamically tested), along with sufficient survivable volume, would have provided the greatest improvement in safety in the accidents reviewed.

3. Impact Energy Management

   Whether through stall speed, energy absorption, or crushable materials, reducing the energy absorbed by the occupant at impact will increase odds of survival in any event and especially when adequate restraints and survivable volume are maintained. Multiple casualties are caused by rapid aircraft deceleration leading to excessive movement of the head and neck, or excessive sink rate leading to the sudden compression of the spinal column, so there are opportunities for either restraint or delethalizing these events through dissipated energy.

4. Prevent Post-Crash Fire

   Half of the accidents examined resulted in post-crash fire. While it can be difficult to determine if the fatalities resulted from fire or blunt-force trauma, multiple autopsy reports indicated that post-crash fire was the primary cause of death. Solutions that address fuel tank integrity, fuel lines and thermal acoustic insulation will be further addressed. It should also be noted that increasing crashworthiness through adequate restraints and improved survivable volume might result in the need for increased post-crash fire protection.

Forward Fit Recommendations

Restraints

1. Dynamically tested restraints perform well but there is good potential to examine statically tested restraints in combination with other improvements.
2. Improve the restraint mount integrity by attaching to primary structure or hard points on the vehicle to ensure that mounting locations do not fail.
3. Improve the seat mount integrity through seat rail reinforcement or tying to primary structure such as wingbox stiffeners, spars, or bulkheads.
4. Introduce restraints that reduce flailing of the occupants.

5. Integrate a load limiter into the belt path.
6. Increase the robustness of the restraints.
7. Integrate an inertia reel in the restraint system.
8. Install airbags into restraint systems.
9. Install pretensioners in restraint systems.

Survivable Volume

1. Designs should consider how structure can assure that the survivable volume will remain whole and intact in the event of low and medium energy crashes.
2. Designs should consider how survivable volume can prevent penetration from large objects (trees, wings, engines, etc.).
3. The survivable volume should not be compromised elastically during the crash event even if volume is apparent after the event.
4. Inflatables, crushable materials, or crumple zones can be utilized to maintain survivable volume.

Impact Energy Management

1. Impact energy can be managed through the use of crushable materials or energy absorbing materials.
2. Utilize the inherent desirable characteristics of the specific materials used in fuselage construction to mitigate impact energy through plastic deformation, buckling, and crumpling (metals) or fiber breaking, splaying and/or pulverization (composites).
3. Reduction of impact energy, whether through controlled stall speeds or speed reducing solutions like parachutes.
4. Create breakaway structures that allow the occupant and their survivable volume to move with the energy.
5. Integrate a fuselage design that allows for plowing and/or object deflection during impact.

Post-Crash Fire

1. Improve the ability of the fuel tank to maintain its structural integrity, whether through a more robust tank, fuel bladders, or other means.
2. Utilize self-sealing fuel lines and hose connections.
3. Integrate thermal acoustic insulation.
4. Replace existing engine with an electric engine.
5. Use low flammable materials for interior coverings, fabrics, insulation, etc.

Retrofit Recommendations

Occupant Protection

1. Integrate pre-tensioners and inertia reels into restraint systems.
2. Install more robust restraints.
3. Install restraints with integrated airbags.

4. Utilize wearable inflatables for occupants.
5. Install Load limiters into the belt path.
6. Examine policy for retrofit of restraints.

Additional Considerations

Reliability

Due to the wide variety of accident scenarios that were analyzed, the working group does not believe that there is one solution, or set of solutions, that if found to be 100% reliable could prove beneficial in 100% of the accidents. The recommendation of the group is that there is significant benefit to be obtained from implementing the solutions presented that have a meaningful probability of improving survivability, even if the solution(s) cannot be shown to have 100% reliability or 100% applicability.

Commercial Off-the-Shelf (COTS) Considerations

There are many technologies available from other industries (e.g., consumer and automotive) that may provide benefits for aviation accident survivability. There needs to be a pathway for these technologies to be incorporated into aircraft crashworthiness systems. Where possible, as a minor alteration, it should be feasible to accept non-aviation specs and compliance for speed of adoption of life saving equipment, and low cost.

Special Considerations for Urban eVTOL Vehicles

There may be additional considerations for eVTOL aircraft due to their design, such as vertical seat loading, and operations, given that they will be operated in densely populated areas, and may have no un-powered means to control flight.

Policy Review and Recommendations

The FAA has rules and regulations in place to protect occupants in the event of a crash. These rules were put into place in the late ‘80s, with the intention of increasing the survivability of occupants in aviation accidents. The rules increased the vertical and longitudinal static requirements and added dynamic requirements, as well as utilized injury criteria to protect the head, chest and spine. There are no lateral safety requirements, though lateral protection requirements would reduce injuries and fatalities. The rules are based more on a component level assessment in order to simplify certification process, however, the new rules only apply to aircraft that have been designed since they were put in place. The older aircraft maintained a certification basis commensurate with the rules in place when it was designed, and as such, the restraint systems tend to be of older qualifications and not as strong as restraints certificated under today’s rules would be. This has led to a lower level of safety for those flying older aircraft, which comprises the majority of the GA fleet. Manufacturers have claimed that the component level certification process has made certification complicated and cost prohibitive, and that possibly a system level process would streamline the process. A system level process would give credit for other areas of crash attenuation built into the structure, such as sub-floor, frangible gear, plow structures or crushable volumes, etc.

Additional Recommendations

ASTM Standards

The recommendations of the working group should be accompanied by a system that allows manufacturers and operators to meet the proposed requirements without restricting innovation. More specifically, this should allow flexibility to implement safety solutions without being overly prescriptive.

ASTM standards for crashworthiness should be appropriately tailored for different levels of aircraft based on occupancy, crash energy potential, and the likelihood of an emergency landing.

NTSB Investigations

As these analyses are conducted, there is a significant lack of data about survival factors aspects, and in many cases, even the ability to determine what type of restraint was used is impossible. This makes looking for trends, usage, or effectiveness, more speculative than quantitative.

In order to more effectively address crashworthiness and survivability factors in the future, it is imperative that the NTSB place greater focus on these areas when conducting investigations on general aviation accidents. Providing greater information in the future will help to ensure that the standards are effectively addressing and reducing fatalities.

In accident investigations in which the NTSB does not participate on site, the investigators who are directly participating, such as FAA FSDO staff and manufacturers, should be encouraged to document crashworthiness factors by photographing the cockpit, seats and restraints. If these photos are taken with, as an example, a ruler, it will help analysis of the impact forces of the crash.

Prior Investigations

The Simula/AGATE Small Airplane Crashworthiness Design Guide culminated several decades of prior effort in the attempt to provide a framework for light aircraft crashworthiness improvements. Many of these recommendations and techniques have great value and rather than restating them here, it is suggested that the safety benefits might be readily achieved by removing barriers to regulatory compliance, thereby encouraging installation and wide spread fleet adoption as discussed earlier in this document.

Crash Data and Safety Culture

Additionally, a lack of GA crash data noted by this group, NASA, AGATE and in NTSB investigations to date, produces analyses and recommendations herein that may be less effective than desired. Where possible, we recommend to remove barriers to integrated data capture on GA aircraft. Useful data can be captured using micro components at a very low cost point. Data is useless unless it will be analyzed and used to improve the applicable regulations on an aggressive annual time frame until fatalities are driven to near zero. A regulatory Safety Culture, addressing manufacturing, installation and usage of technology, has been successfully implemented with desirable results by The Fédération Internationale de l'Automobile and NASCAR.

Cost

Finally, it must be said that cost is the controlling factor for all imagined safety recommendations. Reducing cost at each instance of regulation, compliance, manufacturing, installation, and operation improves the chance for GA fatalities to be reduced. The cost to acquire the applicable standards/specifications needs to be substantially minimized.

Additional Resources

- Simula Technologies, Inc. "Small Airplane Crashworthiness Design Guide." AGATE-WP3.4-034043-036. April 2002.
- DoD. "Military Standard Light Fixed and Rotary-Wing Aircraft Crash Resistance." MIL STD 1290A. September 1988.
- Zimmermann, R.E. et al. "Aircraft Crash Survival design Guide Volume III – Aircraft Structural Crash Resistance." USAAVSCOM TR 89-D-22C. December 1989.
- NTSB. "General Aviation Crashworthiness Project: Phase Two – Impact Severity and Potential Injury Prevention in General Aviation Accidents." NTSR/SR-85/01. March 1985
- Littell, J.D. "Crash Tests of Three Cessna 172 Aircraft at NASA Langley Research Center's Landing and Impact Research Facility." NASA TM-2015-218987. November 2015.
- Carden, H.D. "Correlation and Assessment of Structural Airplane Crash Data With Flight Parameters at Impact." NASA TP 2083. November 1982.

Conclusions

This review of fatal yet survivable general aviation accidents highlighted the crucial need for new and innovative approaches to addressing crashworthiness in light aircraft. The working group recommends that ASTM adopt the recommendations and utilize them in standards development going forward.

Appendix A

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Appendix B

NTSB Accidents Reviewed

ANC10MA068

ANC08FA079

ANC13FA095

ANC15FA049

CEN09FA462

CEN10FA394

CEN11FA420

CEN12FA311

CEN13FA078

CEN13FA196

CEN13FA344

DFW08FA131

ERA09FA289

ERA13MA139

ERA13FA014

ERA15FA277

NYC08FA307

WPR09FA019

WPR10FA326

WPR11FA166