

IMPACT ON AIRCRAFT

Marcílio Alves

Group of Solid Mechanics and Structural Impact
University of São Paulo – São Paulo – SP – Brazil
www.pmr.poli.usp.br/impacto

Carlos Eduardo Chaves

Embraer – Empresa Brasileira de Aeronáutica S/A – São José dos Campos – SP - Brazil
carlos.chaves@embraer.com.br

Robert S. Birch

Impact Research Centre – University of Liverpool – Liverpool - UK
rsb123@liverpool.ac.uk

Abstract. Aircraft structures are subjected to impact loads ranging from small debris to birds strike. This paper offers a modest overview on the subject, presenting some references which help to establish the state of art. Impact is classified according to impact mass and velocity, with the leading mechanisms of an aircraft structure response to these loads being examined. In particular, some aspects of bird strike, i.e. a bird impacting an airplane, are presented, with the induced damage being discussed.

Keywords. Impact, aircraft structures, small debris, bird strike

1. Introduction

In the speed range of common crash phenomena, say from 0 to 30km/s, many features not found in the quasi-static analysis of structures are to be considered. For low impact velocities, say up to 20m/s, the main aspect one needs to take care of is the material response to dynamic loading, which can be significantly affected by the resistance offered by dislocation mechanisms to fast moving. Indeed, for some materials, their strength can be so affected that the flow stress doubles. This range of velocities can easily be found in car and train crashes, ship collisions and hard landing of aircraft.

For higher velocities, say between 100 km/h and 1000 km/h, as found in the impact of aircraft on buildings or of missiles on targets, or for the extreme velocities of meteorite impacts on space vehicles, shock wave features needs to be taken into account and the material behaviour is best described by hydronic relations.

Generally, the impact process can be considered as being either boundary-controlled or wave-controlled. Boundary-controlled conditions are assumed to apply if the impact duration is greater than the time required by the transient flexural waves to reach the boundaries. This is the case if the impact duration is larger than the half period of the lowest vibration mode. Here, the impact response is strongly dependent on the geometry of the target and can sometimes be analysed using a quasi-static model. These assumptions are not valid if the impact duration is of the same order or shorter than the transition time for through-thickness waves in the plate or longitudinal waves in the projectile. In such cases, the impact event is said to be wave-controlled and the planar geometry of the target is less important.

As indicated in Reference [25], two-thirds of the aircraft accidents in Canada in the seventies occurred within narrow speed ranges associated with landing and take-off. This figure is likely to be still applicable to other aircraft crash data around the world so that, in many cases, aircraft impact is in the low to medium range of impact velocities. In this range of velocities, it is all feasible to add some structural features to an aircraft such that the major design requirement of maintaining structural integrity of the cabin-fuselage is met. In this scenario, the improvement of the capability of aircraft to sustain impact loads is worth to be pursued and, indeed, the airworthiness area has been received continuous attention from governmental ruling bodies and from aircraft manufacturers. Accordingly, aircraft designers must consider the effects of severe impact loading conditions when there is a potential risk of causing extensive structural damage that may compromise cargo, crew and passengers safety.

These days, sophisticated methods of analysis are available so that the design of a structure can be tailored towards an adequate response to these extreme impact loads. Even so, the aim of building airworthy aircraft capable of mitigating the effects of all types of impact damage is far from completion. However, the design and manufacturing of an impact resistant crashworthy aircraft remains an important topic for consideration and the prospect of more stringent design codes is something that the aerospace industry must be prepared to address in the future.

In this context, this paper offers a modest overview on the subject of structural impact as applied to aircraft structures, from dropped tools to high velocity bird strike. It also aims to bring awareness to the technical community of some peculiar features of this important problem. Section 2 presents a broad impact classification for aircraft, with section 3 describing some impact scenarios. Sections 4 and 5 comments on types of damage caused to the skin and structure of an airplane and on the absorption of impact energy. Bird strike is another important feature of impact in aircraft and are approached in section 6, followed by conclusions and some references in the field.

2. Impact classification

In order to offer an overview on the impact of aircraft structures, it is opportune a classification based on the mass and velocity of the projectile hitting an aircraft. Thus, a small hard mass (order of grams) travelling at high speed (hundreds of meters per second) would likely cause highly local damage and material penetration. At these speeds, heavier but softer masses (order of kilograms - typical from birds), are more likely to cause significant large global plastic strain with extensive structural deformation and material failure at the boundaries. Much heavier masses are also possible, when the aircraft itself impacts a target [1]. A more detailed classification can be obtained when considering specific objects and angle of incidence, as listed in Table 1.

Description	Energy (J)	Mass (g)	Velocity (m/s)	Circumstances
tool drop	6	330	6+	Maintenance work
removable element drop	4	220	6+	Cargo handling
maintenance component	16	910	6+	Maintenance work
hail (up to 51 mm diameter)	43	62	37.3	Take-off and landing, flight, taxiing
bird strike	3.8-81 (kJ)	1800	65-300	Take-off and landing, flight
runway debris	2-40	9	20-94	Take-off and landing, flight, taxiing
concentrated load	50	-	Static	Maintenance, cargo handling

Table 1. Common types of projectile impact on aircraft.

Table 1 covers a wide range of impact speeds (0 to 300m/s) and masses (1 to 2000g, appr.), but the impact of the aircraft itself is excluded. An impact can be perpendicular or oblique and may have the added velocity of the aircraft flight speed in the appropriate part of the flight envelope. Flight envelope is a velocity diagram in the various possible movement directions of an aircraft. For impact velocities within its boundaries, fatal accidents are less likely to occur. Conversely, for impact speeds falling outside this flight envelope, the energies involved are so high that fatal accidents are expected.

For impact cases such as hail or bird strike, where there is a direct risk of causing an aircraft crash, sources of data are available through the various national aviation authorities who closely monitor reportable impact events. A complete collection of data is difficult to obtain, especially as much information is likely to be classified as internal reports. Also, there appears to be less information available in the open literature on the impact parameters and effect of maintenance accidents or small runway debris.

3. Crash scenarios

Table 2 collapses many accidents into a few crash scenarios. As pointed out in Reference [18], accidents that are initiated when the aircraft is on the ground are rarely fatal, in contrast with accidents at high speed and large impact angles. In between, occupant survivability is possible depending on the surrounding hazards.

Candidate crash scenario	Impact conditions	Accident type	Terrain	Hazard
Ground to ground overrun	Low sink speed Low forw. velocity Sym. a/p attitude Gears extended	Takeoff abort Landing overrun	Runway Hard ground	Mound Slope Slab Light stanchion
Air-to-ground, hard landing	High sink speed Landing velocity Sym. a/p attitude Gears extended	Hard landing Undershoot	Runway Hard ground	None
Air-to-ground, impact	High sink speed Landing velocity Unsym. a/p attitude Gears extend./retard.	Uncont/controlled Grd. Collision Stall Undershoot	Wooded Hilly	Trees Slopes Buildings

Table 2. Identification of candidate crash scenarios [18].

It is also important to consider runway debris like nuts, bolts, washers, safety wire, tools, nails, badges, pens, pencils, stones, sand, pieces of wood or plastic, ice, tyre tread and bits of paving, identified as common items related to accidents [2]. Potentially, they can become projectiles if kicked up by the tyres of the aircraft or by the engine jet. Primarily, the main danger is through the ingestion of debris into the engine intake and civil airports operate strict housekeeping rules in order to reduce this risk. An initial literature search for further details on this problem has revealed little quantitative data on the size, expected velocity and probability of occurrence of this type of impact.

Runway debris was considered to be the major cause of one of the most famous accidents in the recent history, where a Concorde aircraft exploded in the air killing 113 persons. A report from the French Government [3] pointed out that the left tyre of this aircraft was damaged when passed over a strip of metal that had fallen onto the runway from another aircraft. Parts of the tyre were thrown up onto the aircraft structure at high velocity, this initiated a fire and later an explosion. An important lesson to be learned here is that an apparently soft light piece of debris, such as tyre fragment, can cause severe damage if sufficiently high impact velocities are attained.

4. Damage

The location of an impact on an airframe structure is also important, and whether the impact is close to some reinforcement such as a stiffener or support, or when in the centre of a flexible panel membrane, very different damage levels can result. Chisman and McNaughtan [4] showed that the energy to penetrate a thin airframe skin (aluminium) can be reduced by up to 50%, approximately, accordingly to the impact location.

Types of damage can be either global, in areas remote from the impact site, or highly localised, very close to the impact site itself. Global damage is likely in between structural boundaries (stiffeners) where there are large changes in rigidity. Transient flexural waves may propagate from the impact site and be reflected back from a rigid boundary to become superimposed on another on-coming wave.

One source of damage is the one due to hailstones, whose formation in the atmosphere is a complex process and not readily predictable. During the formation process, the hail is suspended in the up draught of the cooled region of a cloud before falling to ground level. The terminal velocity of a particular hail stone is dependent on the size and density of the local atmosphere.

Of 272 damaging hailstone impacts, which were reported by the United States Air Force from 1951 through to 1959 [5], 46% occurred above 20,000 ft (i.e., at flight speed) with several incidents of 76 mm -102 mm diameter hail encounters between 31,000 ft and 37,000 ft. Figure 1 shows that the majority of cases were less than 26 mm diameter although experimental research work [5] has examined diameters of up to 51 mm and assuming a density of 0.9 g/cm³, the terminal kinetic energy associated with each diameter is also presented in Figure 1.

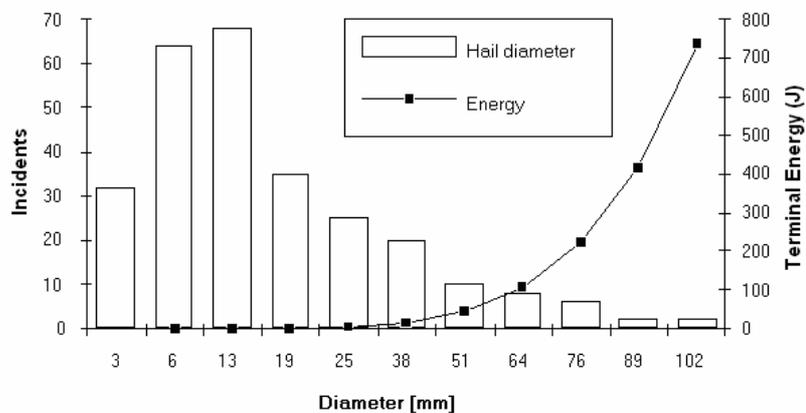


Figure 1. Hail velocity (272 damage incidents, 1951-1959, US Air Force)

While on the ground, an aircraft is susceptible to vertical impacts on the upper surface and progressively oblique towards the side. In flight, these areas are again at risk from vertical and oblique impacts that will have a combined horizontal velocity component of the aircraft. Steep take-off/landing angles and atmospheric up draughts, which are present during the formation of hail, means that it is possible the lower surface of an aircraft to be impacted.

To prevent local severe damage such perforation, which disrupts many aspects of a flight, e.g. cabin pressure, some technical solutions have been tested, leading to new conceptions for the fuselage protection, like the one illustrated in Figure 2.

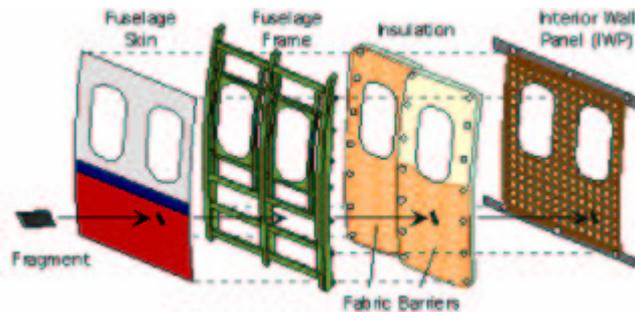


Figure 2. A protection system for the fuselage [10].

The insertion of the fabric barrier illustrated in Figure 2 can be also used for the protection of turbines or its fragments that may be generated by depletion of its blades, which results in severe damage, Figure 3.



Figure 3. Structural damage in an aircraft caused by blade failure [11].

Avery [7] conducted a series of high velocity impact tests on a range of aluminium and carbon fibre/epoxy plates. For the case of impact on aluminium structures, the conclusions were drawn that the velocity for the onset of damage increases with the angle of obliquity and that, for a given impact angle, the size of the damage zone is greatest at the perforation limit. Also, the maximum size of damage increases with angle of impact and Avery's data indicates that an elongated damage zone occurs at angles of approximately 60° and above.

Avery [7] also proposed a ballistic limit model for carbon fibre reinforced plastic impacted by mild steel fragments. This perforation model suggests that perforation can occur for any angle of impact below 90° . Indeed, Avery conducted tests using impact angles between 0° and 70° and observed perforation in all cases.

Changes in curvature also affect the flexural stiffness of a structure and alter the area of contact between projectile and target. Previous work has shown that for low velocity impact loading by a heavy mass on, say, a relatively thick panel, the damage initiation threshold is strongly dependent upon the flexural stiffness of the structure. Increasing the curvature (stiffness) of a panel will also increase its stiffness and is likely to result in an increase in the damage threshold energy.

Currently, the response of composite materials to oblique impact loading has received very little attention. Madjidi et al. [8] conducted a series of low velocity impact tests on a number of chopped strand mat/polyester resin plates. Their data indicated that, for a given impact energy, increasing the angle of impact results in a decrease in the overall level of damage. Very few studies have investigated the effect of oblique impact loading on the residual load-bearing properties of composite materials. Jenq et al [9] conducted normal and oblique high velocity impact tests on a $(0^\circ, 90^\circ, 0^\circ)$ glass fibre reinforced epoxy and showed that normal impact loading was more detrimental to the load-bearing capacity of the composite.

High velocity impact tests on a thin-skinned boron/epoxy honeycomb sandwich structure and a thick carbon fibre epoxy laminate again highlighted a distinct impact angle dependency [9]. Damage size tended to increase with increasing impact angle. However, there appeared only to be a moderate increase in damage size in passing from a normal impact to obliquity angle, θ , of 60° and so, for most impact angles, the damage zone is relatively small.

As an illustration of severe damage in aircraft structures, Figure 4 shows the perforation of an aircraft skin by a steel sphere travelling at 258m/s [21].

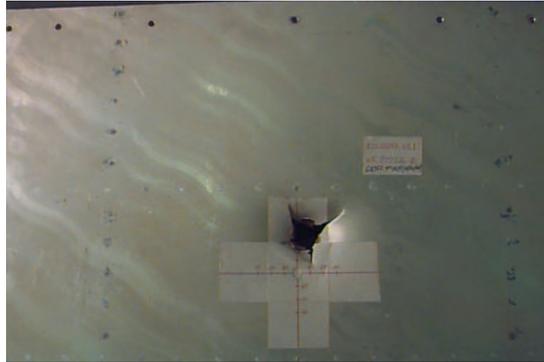


Figure 4: Aluminium sheet perforated by a projectile travelling at 258m/s [21].

5. Impact energy absorption

The design of an aircraft bearing in mind its capability of absorbing impact energy has been the subject of little research. Reference [15] presents some consideration about the use of composite materials to absorb impact energy. References [16], [17] and [18] deals with numerical analysis and experimental data about the impact of fuselages and helicopters in different configurations. Of course that the impact on structures can lead to material failure and Reference [19] approaches the subjected of local material separation.

There are various ways to mitigate the impact energy released in the event of a crash so that less damage can be inflicted to the accident scenario. Impact energy absorbers have been recently studied in detail in the context of the automotive industries. At some extent, these studies have also drawn the attention for possible application in the aeronautical industries, such that full crash simulation are now being explored [12]. Reference [13] presents a numerical analysis, motivated by experimental tests, of a helicopter support structure made of a composite material. A similar task is pursued in Reference [14], whose authors modeled numerically an aircraft substructure made from composite materials.

6. Bird strike

A major concern on the impact of aircraft is related to the damage birds can cause. The impact severity is so huge, as indicated in Figure 5, that regulating bodies, e.g. Federal Aviation Administration – U.S.A., demand a series of experimental tests involving bird impact and aircraft components.



Figure 5. Impact of a bird on the rear wing of an aircraft.

The common case of a 4 kg bird impacting an aircraft whose speed is 870km/h (242m/s), implies an energy of 117 KJ, which ideally has to be absorbed by the structure with minimum damage. This prompts the search for strong structures but still light. Despite the fact that real structural tests on aircraft are quite prohibitive in terms of costs, it is interesting to mention that such a test is actually performed, as seen in Figures 6 and 7, the last one representing a section of an aircraft subjected to a bird impact.



Figure 6. Experimental apparatus for impact tests [10].



Figure 7. An aircraft nose after being impacted by a testing bird.

Airworthiness regulations require that airliners must withstand an impact from a 1.8 kg (4 lb) bird when the velocity of the airplane (relative to the bird along the airplane's flight path) is equal to cruise velocity at sea-level or 0.85 cruise velocity at 8000 ft, whichever is the more critical.

Bird strike is a very significant and nearly common problem. For instance, during the period 1981-1985, European airlines operating world-wide reported over 7500 incidents of bird strikes [6] representing a rate of 5.1 per 10,000 aircraft movements (two movements per flight). Of these, 17% were on an engine and 1.3% of these were cases where more than one engine was struck. As in the case of hail, steep take-off angles expose lower surface of the aircraft to a possible oblique bird strike.

Of importance for the civil aviation, the bird strike is a subject which needs further research, both on modeling as well as on experimental procedures. Accidents with birds involving aircraft offer a wide range of energies and impact configurations which are difficult to model. Hence, there should be an interplay between experimental procedures [19,20] and numerical approaches [20].

Figure 8 shows the major areas of a commercial aircraft which have to be certified against damage from bird strikes. It can be seen at once that the amount and cost of such tests are quite significant, which prompts the development of more accurate material models and the knowledge about the intricate details of the interaction between the structure and the projectile.

The high costs which need to be met for performing impact tests on aircraft fuselages prompt many researches dealing with, for instance, perforation and, hence, with material failure, from small objects [22, 23] and even from drops of water from the rain [24].

7. Conclusions

In this article, some features of the impact on aircraft were highlight. This is an important subject in considering the fatal consequences for passengers and the huge economic losses associated with crash scenarios. Technically, the impact analysis can be rather troublesome due to various effects like strain rate and temperature. Also, the high energies involved in impact events often leads to material failure, another complicated feature.

Nowadays, the high costs of experiments dealing with aircraft impact dictate a shift towards numerical simulations. Even though, it is not possible to rely exclusively on their results so experiments are to be performed side by side with numerical analysis. Also, sophisticated material models are necessary in order to improve the accuracy of the simulations. It seems evident that an interplay among theoretical models, simulation and experiments are necessary in order to well predict the various features on an impact event involving aircraft.



Figure 8. Regions in an aircraft that have to be tested against impact of birds.

8. References

1. T. Wierzbicki and X. Teng, How the airplane wing cut through the exterior columns of the World Trade Center, *International Journal of Impact Engineering*, 28, p. 601-625, 2003.
2. FAA Report, Debris Hazards at Civil Airports, FAA-AC-150/5380-5A, 1981.
3. Ministère de l'équipement des transports et du logement. Rapport interim BEA f-sc000725ae, December 2000.
4. Chisman S. W. and McNaughtan I. I., The Hail Impact Resistance of Aluminium Alloy Aircraft Structure, RAE Technical report 72170 August 1972.
5. Foster D., Aviation Hail Problem, World Meteorological Organisation, Technical note No 37, WMO No 109, TP.47., 1961
6. Thorpe J. Analysis of Bird Strikes Reported by European Airlines 1981-1985, CAA Paper 92004, Civil Aviation Authority, London, 1992.
7. Avery J.G., Design manual for impact damage tolerant aircraft structures, AGARDograph 238, 1981.
8. Madjidi S., Arnold W.S. and Marshall I., damage tolerance of CSM laminates subjected to low velocity oblique impacts, *Composite Structures*, 34, 1996, 101-116.
9. Jenq S.T., Wang S.B. and Wu J.D., Effect of normal and oblique impact damage on the strength degradation of composite laminates, *Proc. ICCM VIII*, 1991, Honolulu, 1-9.
10. http://www.sri.com/poulter/air_safety
11. Norman F. Knight Jr, Navin Jaunky, Robin E. Lawson e Damodar R. Ambur, Penetration simulation for uncontained engine debris impact on fuselage-like panels using LS-DYNA, *Finite Elements in Analysis and Design*, 36(2), p. 99-133, 2000.
12. M. Bossak and J. Kaczkowski, Global/local analysis of composite light aircraft crash landing, *Computers & Structures*, 81, p. 503-514, 2003.
13. M.A. McCarthy e J.F.M. Wiggensraad, Numerical investigation of a crash test of a composite helicopter subfloor structure, *Composite Materials*, 51 (2001) 345-359.
14. Rodney S. Thomson e Murray L. Scott, Experience with the finite element modelling of a full-scale test of a composite aircraft control surface, *Composite Structures*, vol. 50, p. 331-345, 2000.
15. C.M. Kindervater e H. Georgi, Composite strength and energy absorption as an aspect of structural crash resistance, in *Structural Failure*, N. Jones e T. Wierzbicki (editores), p. 189-235, 1993.
16. E. Haug, F. Arnaudeau, J. Dubois e A. de Rouvray, Static and dynamic finite element analysis of structural crashworthiness in the automotive and aerospace industries, in *Structural Crashworthiness*, N. Jones e T. Wierzbicki (editores), Butterworth, p. 175-217, 1983.
17. R.C. Tennyson e J.S. Hansen, Study of the crash behaviour of aircraft fuselage structures, in *Structural Crashworthiness*, N. Jones e T. Wierzbicki (editores), Butterworth, p. 218-258, 1983.
18. G. Wittlin, Aircraft crash dynamics: modelling, verification and application, in *Structural Crashworthiness*, N. Jones e T. Wierzbicki (editores), Butterworth, p. 259-282, 1983.
19. C. Ruiz e R. Duffin, Experimental study of soft body impact at subordnance velocities, *Experimental Mechanics*, editor I.M. Allison, p. 143-148, A.A. Balkem, Rotterdam, 1998.
20. T.H. Antoun, P.R. Gefken, B.S. Holmes, and S.W. Kirkpatrick, "Description of a Six-Inch Gas Gun Facility for Soft Body Impact," *Proceedings 43rd Annual Meeting of the Aeroballistic Range Association (ARA)*, Paper No. 50, Sept. 28 to Oct. 2, 1992 (home page <http://www.sri.com/poulter/composites/bird.html>).
21. C. E. Chaves, K. Schwarzmeier, F. Olmi, E. Araújo e P. Buis, Small debris impact simulation using MSC.Dytran – Part II, M.S.C. Aerospace Users Conference, 2002.
22. W. S. Walston, R. Darolia e D. A. Demania, Impact resistance of NiAl alloys, *Materials Science and Engineering A*, vol. 239-240 (1-2), 1997, p. 353-361.

23. Damodar R. Ambur, Navin Jaunky, Robin E. Lawson e Norman F. Knight, Jr. Numerical simulations for high-energy impact of thin plates, *International Journal of Impact Engineering*, vol. 25 (7), p. 683-702, 2001.
24. William F. Adler, Rain impact retrospective and vision for the future, *Wear*, vol. 233-235, p. 25-38, 1999.
25. R.C. Tennyson and J.S. Hansen, Study of the crash behaviour of aircraft fuselage structures, p. 218-258, in *Structural Crashworthiness*, edited by N. Jones and T. Wierzbicki, Butterworths, 1983

9. Additional bibliography

The references below were collected from various chapters of the book *Structural Crashworthiness*, edited by N. Jones and T. Wierzbicki, Butterworths, 1983 and they are not always easy available. Also, they have not been read by the present authors but have been selected as a way to complement and expand the references quoted before.

26. Aircraft Crash Environment and Human Tolerance, Vol. II, Aircraft Crash Survival Design Guide, Simula, Inc. USARTC-TR-79-22B (1980)
27. Aircraft crash survival design guide, U.S. Army, Vol. I, 1989, ERAU reprint
28. Alfaro- Bou, E. and Vaughan, V. L., Jr., Light Airplane Crash Tests at Impact Velocities of 13 and 27 m/s, NASA Technical Paper 1042 (1977)
29. Carden, H. D. and Hayduk, R. J., Aircraft Subfloor Response to Crash Loadings, SAE Paper 810614 (1981)
30. Castle, C. B. and Alfaro-Bou, E., Light Airplane Crash Tests at Three Flight-Path Angles, NASA Paper 1210 (1978)
31. Castle, C. B., Full-Scale Crast Test of a CH-47C Helicopter, NASA TM X.3412 (1976)
32. Cronkhite, JD, Crashworthy Design Concepts for Airframe Structures of Light Aircraft, SAE Paper 810613 (1981)
33. Federal Aviation Regulations, Part 25-Airworthiness Standards: Transport Category Airplanes, FAA, Washington
34. Gamon, M. A., General Aviation Airplane Structural Crashworthiness User's Manual, Vol. I, Program KRASH Theory, FAA Report No. FAA-RD-77-18 (1978)
35. Gamon, M. A., Wittlin, G. and LaBarge, W. L., General Aviation Airplane Structural Crashworthiness User's Manual; Vol. II, Input-Output, Techniques and Applications, FAA Report No. FAA-RD-77-189 (1978)
36. Hayduk, R. J. and Thomson, R. G., Simulation of aircraft crash and its validation, in Proc. of the AIAA Eleventh Annual Meeting, Washington, D.C. (1975)
37. Hayduk, R. J., Thomson, R. G., Wittlin, G. and Kamat, M. P., Nonlinear Structural Crash Dynamics Analysis, SAE Paper 790588 (1979)
38. Melosh, R. J. and Kamat, M. P., Computer simulation of light aircraft crash, *AIAA Journal of Aircraft*, 14 (10), 1009 (1977)
39. Melosh, R. J., Crashworthiness engineering of automobiles and aircraft progress and promise, *AIAA Journal of Aircraft*, 14 (7), 693 (1977)
40. Cronkhite, J. D. and Berry, V. L., Crashworthy Airframe Design Concepts-Fabrication and Testing, NASA, 1982
41. Reed, W. H., et al., Full-Scale Dynamic Crash Test of a Lockheed Constellation Model 1649 Aircraft, Aviation Safety Engineering and Research, FAA Technical Report ADS-38, Washington, D.C. (1965)
42. Saczalski, K., Singley, G. T. III, Pilkey, W. D. and Huston, R. L., *Aircraft Crashworthiness*, Univ. Press of Virginia, Charlottesville (1975)
43. Singley, G. T., US Army Crashworthiness Program, SAE Paper 810615 (1981)
44. Tennyson, R. C. and Bird, J. W., The need for improved aircraft crashworthiness design, *Journal of Canadian Aeronautics and Space Institute*, 23 (5), 269 (1977)
45. Tennyson, R. C., Nanyaro, A. P., Teichman, H. C. and Hansen, J. S., *Crashworthiness of Light Aircraft Structures*, Final Report, Transport Canada Research and Development Centre (1981)
46. Thomson, R. G. and Goetz, R. C., NASA/FAA general aviation crash dynamics program-a status report, in Thlentieth Structures, Structural Dynamics and Materials Conf, AIAA/ASME/ASCE/AHS, p. 224 (1979)
47. Thomson, R. G. and Goetz, R. C., NASA/FAA general aviation crash dynamics programa status report, *Journal of Aircraft*, 17 (8), 584 (1980)
48. Vaughan, V. L., Jr., and Alfaro-Bou, E., Impact Dynamics Research Facility for Full. Scale Aircraft Crash Testing, NASA TN D-8197 (1976)
49. Widmayer, E. and Brende, O. B., Commercial Jet Transport Crashworthiness, Boeing Airplane Co., NASA CR 165849, FAA Report DOT/FAA/CT-82/86 (1982)
50. Winter, R., Cronkhite, J. D. and Pifko, A. B., Crash simulation of composite and aluminium helicopter fuselages using a finite-element program, in Thlentieth Structures, Structural Dynamics and Materials Conf, AIAA/ASME/ASCE/AHS, p. 233 (1979)
51. Winter, R., Pilko, A. B. and Cronkhite, J. D., Crash simulation of composite and aluminium helicopter fuselages using a finite element program, *Journal of Aircraft*, 17 (8), 591 (1980)
52. Wittlin, G. and Gamon, M. A., A Method of Analysis for General Aviation Airplane Structural Crashworthiness, FAA Report FAA-RD-76-123, Lockheed-California Company, Washington, D.C. (1976)
53. Wittlin, G., Analysis of aircraft dynamic behaviour in a crash environment, in Proc. Thlenty-third Structures, Structural Dynamics and Materials Conf, AIAA/ASME/AS. CE/AHS, p. 316, New Orleans (1982)
54. Wittlin, G., Transport Aircraft Crash Dynamics, Lockheed-California Co., NASA CR 165851, FAA Report DOT/FAA/CT-82/69 (1982)