Crashworthy Composite Fuselage Section Concept for Next Generation General Aviation

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ABSTRACT

Advances in aircraft crashworthiness can be achieved by the development of crashworthy composite fuselage concepts. To attend the design requirements that will be established by the next generation of general aviation aircraft, the present work presents an innovative composite fuselage section concept that besides its added crashworthiness features represents a great potential for weight and manufacturing costs reduction.

INTRODUCTION

The use of general aviation aircraft for passenger transportation is increasing rapidly. It has been estimated that more passengers annually travel in general aviation aircraft than in all the commercial air carriers combined, and NASA research program SATS (Small Aircraft Transportation System) presents a great insight of the future. [1,2]

The SATS research roadmap encompasses on-demand, widely distributed, point-to-point air mobility, through hired-pilot modes in the nearer-term, and through self-operated user modes in the farther-term. The nearer-term concept is based on aircraft and aerospace technologies being developed to make the use of thousands of smaller neighborhood airports and their runways more useful in more weather conditions, in commercial hired-pilot service modes. The farther-term vision is based on technologies that could be developed to simplify or automate many of the operational functions in the aircraft and the airspace for meeting future public transportation needs in self-operated modes.

The development of fanjet engines in smaller sizes and a new generation of piston diesel engines are the most important driver factors of these new personal aircraft market. Engine makers have shown recently that their product is already mature and suitable for widespread use and the market is now expecting the introduction of the first players of this new generation of small, cabin-class light aircraft, offering speed, range and payload at affordable price, and which will bring general aviation standards to a new level.

The customers of this new personal aircraft market will have very high expectations related to safety. To achieve the SATS vision for affordable, safe, 21st century inter-city transportation by way of using smaller aircraft and smaller airports, innovations in crashworthiness technologies are vital. The current accident rate, that has remained the same for the last two decades, won’t be further accepted. Crash survivability will need to be comparable to highway auto accidents, and the public perception that general aviation is not safe will need to be changed. The same integrated occupant safety features (energy absorbing structures, smart restraint systems, airbags, etc.) current offered in most automobiles will need to be available in these new aircraft, and the slow pace of improvement of general aviation aircraft crashworthiness that contrasts sharply with the progress in improving automobile crashworthiness will need to be reversed.

Recently the NASA AGATE “Advanced General Aviation Transport Experiments” published the results of its crashworthiness research program, which had the objective to develop and validate advanced crashworthiness concepts and design methods for general aviation [3-5]. The following themes were covered by the project, which was focused on a composite aircraft concept: inflatable restraints, computer modeling, energy absorbing subfloors, seat certification, aircraft airbag sensors, energy absorption of composite sandwich panels, thermoplastic energy
absorbing subfloor structures, and shoulder belt pretensioners.

The AGATE crashworthiness research definitely proved that advances in aircraft crashworthiness can be achieved by the development of crashworthy composite fuselages. The present work develops further the theme and presents an innovative composite fuselage section concept that besides its added crashworthiness features represents a great potential for weight and manufacturing costs reduction. The objective is to attend the design requirements that will be established by this next generation of light aircraft, providing a concept that improves safety and survivability.

**DESIGN CONCEPTS**

**STRUCTURE CRASHWORTHINESS** - The design of an aircraft structure involves a series of commitments with respect to payload, performance, aerodynamics, strength, simplicity of fabrication, economics, and the additional requirement of crashworthiness. As more attention is directed towards airframe crash resistance throughout the design stages, methods and techniques of construction shall improve so that an adequate crashworthy structure will be achieved with acceptable weight, cost, and performance penalties.

The term “crashworthiness” provides a measure of the ability of a structure and any of its components to protect the occupants from injury during a survivable crash. In a broad sense, it includes such considerations as maintaining the structural integrity of the fuselage; attenuating the crash forces acting on occupant bodies; preventing items of mass from breaking free and becoming injury producing missiles; providing exits for the escape of occupants after the crash; and reducing postcrash fire, submersion, and other hazardous conditions that may be encountered in an accident.

The probability of occupant survival is increased if proper attention is given to the following features during initial design: airframe protective shell around occupants; adequate tie down strength for occupants, cargo and equipment; non-injurious occupant acceleration environment; non-injurious occupant environment hazards; elimination of postcrash fire; adequate emergency escape and rescue provisions.

The fuselage subfloor is one of the most important structures that can help protect occupants from high decelerations by absorbing energy during the crushing process that occurs in vertical impacts. This structure must be allowed to crush and deform in a controlled and predictable manner, presenting large plastic deformation during the crash and minimizing the forces and accelerations imposed upon occupants. Metal structures generally accomplish this through the process of instability failures followed by large plastic deformations. Some components are also capable of absorbing energy following compressive collapse. Also, the subfloor design should possess postcrash structural integrity and should function properly under combined load effects resulting from varying impact conditions.

However, general aviation aircraft have little crushable airframe structure and limited subfloor height, thus considerable work has been done to investigate various subfloor structural concepts capable of sustaining normal flight and landing loads while providing significant energy absorption during a crash with vertical velocity. The design criteria recommended by FAR Part 23 is an occupant vertical acceleration less than 20g at a crash with vertical velocity of approximately 30fps [6].

The current general approach is to follow design solutions developed for helicopter subfloor structures [7]. One interesting concept developed by the NASA, consists in providing the aircraft with energy absorbing composite keel beams. NASA initially studied the use of a composite sine wave beams replacing aluminum floor spars on an existing aircraft. The objective was to come up with a retrofitable design solution that could improve crashworthiness of operating aircraft [8].

Composite sine wave beams are considered to be an optimum design for energy absorption. Their use has long being considered for helicopter subfloors and more recently they were chosen by the European program CRASURV (Design for Crash Survivability) as the ideal subfloor concept for a composite crashworthy commuter type aircraft. [9-12]

However, with the objective of increasing design robustness and reducing manufacturing costs, NASA concept evolved, and the sine wave beams were replaced by foam filled cellular beams. These cellular beams consist of an inline assemblage of rectangular cross section cells, forming the cellular core of a sandwich beam. The use of the cellular beams accounted for a more flexible possibility to manipulate the crush response, by altering the cell geometry and cell-wall properties, without sacrificing stability and post-crush integrity. [13]

**COMPOSITE MATERIALS** - The design concept of a fuselage for next generation general aviation aircraft shall be characterized by the fact that aluminum is completely replaced by composites. This is a tendency of the last two decades, which have seen composites being increasingly used to build aircraft structures, particularly in helicopters, light aircraft, commuter planes and sailplanes, because of numerous advantages including low weight, high static and fatigue strength, the possibility to manufacture large
integral shell structures and in some cases better fire resistance compared to aluminum.

Since the application of composites to aircraft fuselages has become feasible, the crashworthiness aspects related to composite structures have become a serious issue. In opposition to aluminum, a material with considerable capacity for plastic deformation, a very important characteristic of materials such as carbon fiber/epoxy is that they are inherently brittle and usually exhibit a linear elastic response up to failure with little or no plasticity. However, when suitably triggered to fail by delamination and compression crushing, composites may exhibit a very high energy absorption capability. When crash loading is taken into consideration since the early design stages of a composite fuselage, and instead of simply copying the traditional metallic constructions the composite design explores the material properties on all its facets, crashworthy concepts can be obtained that far overcome the traditional aluminum ones.

Part of the difficulty in designing with composites has to do with having the appropriate database of material properties. The properties of aluminum alloys are readily available for designers, but that has not been the case for composites. Much of the composites design data has to be developed through testing by the aircraft manufacturer and presented to the certification authorities for approval. However, following also a NASA AGATE research program, the FAA recently published a new policy for the standardization of composite materials, which enables the use of shared databases of material properties by Part 23 aircraft [14-18]. The FAA initiative was the first step for a cost reduction and streamlining of a general aviation composite aircraft certification, and more policies are being expected for the near future. Main topics to be covered includes: structural strength substantiation, damage tolerance and maintenance practices, bonded joints, and advanced material forms and processing.

SANDWICH STRUCTURES - The challenge of making a structure as light as possible without sacrificing strength is fundamental in aircraft design. Inevitably this requirement leads to the need to stabilize thin surfaces to withstand tensile and compressive loads and combinations of the two, in shear, torsion and bending. The use of thin skins with a stabilizing core between them, which is termed sandwich panel, has proven to be a very efficient construction principle in a variety of aerospace applications.

Panels - The performance of a sandwich panel depends primarily upon the efficiency of the facesheets and the distance between them. A great distance between facesheets produces a correspondingly great geometrical moment of inertia, thus leading to high bending stiffness. Since this arrangement subjects the core of the sandwich to a relatively small amount of stress, its weight can be reduced significantly. However, extremely thin-walled panels present a relative sensitivity for impact damage and to fully realize the weight-saving potential of such structures, one must first understand its damage tolerance characteristics.

When used as fuselage skins, damage to sandwich panels generally results from high-energy events, such as ballistic penetration, and low-velocity impacts, such as tool drops. Generally low-velocity impacts are of more harm since many times, damage modes as delamination, core crushing and facesheet debonding are not visually detectable. The current certification praxis consists in inflicting impact damages on a structure, to the extent that the damage is barely visible, and demonstrating by testing that the damaged structure can withstand ultimate static load and one lifetime of spectrum loads. For larger impact damages, which are clearly visible, the structure must sustain spectrum loads for inspection interval and maintain a residual strength of at least limit load [19].

An interesting new concept, especially for large diameter fuselages, is to consider a sandwich panel where the inner facesheet is the main load carrying structure and the outer skin is only a thin damage detector layer. The core provides stability to the facesheets and together with the outer facesheet guarantee the damage resistance necessary to avoid that low energy impacts affect the integrity of the inner skin. Such a sandwich panel is implemented for example by the SoFi (string outside frame inside) concept, in which the load carrying capacity of the inner skin is added by outside located stringers and inside located frames. The concept avoids the crossover points of stringers and frames but might have undesired effects of an asymmetric sandwich panel lay-up. [20-22]

Cores - Honeycomb core materials, made of aluminum or Nomex, have been largely used for aerospace sandwich construction. They have a great potential for performance with regard to weight, due to the amazing compression modulus with minimum material use. However, an important disadvantage of honeycomb cores is that they may fill up with water under certain circumstances, the water in the honeycomb cells may freezes and expands, at low temperatures, damaging adjacent cells. For maintenance activities, that means that the honeycomb core components have to be inspected more frequently to verify the amount of carrying water. The costs of servicing and repairing these components can diminish the positive aspects of the low structural weight.

An attractive alternative to honeycomb cores are PMI (Polymethacrylimide) foams, generally known as Rohacell. These foams present isotropic mechanical properties, better acoustic and insulation characteristics, very high energy absorption and reduced costs of processing. Unfortunately they also have high moisture absorption, which is very detrimental. However, if Rohacell foam cores are used in
combination with liquid resin infusion manufacturing technologies, the outside of the foam core is sealed with a thin resin film that effectively stops the water absorption.

[23]

**FUSELAGE SECTION CONCEPT**

The here proposed fuselage section for a next generation general aviation aircraft is presented by Figure 1. The concept could be implemented either for an aircraft of the microjet category or for a new category of cabin class diesel piston twins.

![Figure 1 - Fuselage Section Concept](image1)

The section concept consists basically of three major composite components: a left and right hand skin and the floor structure (inboard and outboard floor beams with integral seat fittings and floor stanchions).

The fuselage skins must be seen as a multi-functional system constituting the outer shell of the fuselage pressure vessel, a fire resistant and impenetrable protective shell enclosing the occupants in a crash event, and a thermal and acoustic insulator.

As presented by Figure 1, the skin halves are sandwich panels forming a monocoque structure. Although only a 700mm section is being considered in the study, the complete pressurized region of the fuselage could consist of only two fuselage halves, each one containing integral forward and aft pressure bulkheads. The skin panels shall have carbon fiber faces and the core could be either honeycomb or PMI foam, the preferred solution being dependent on the chosen manufacturing process.

A non-circular cross-section contour (Figure 2) was chosen to maximize internal space and occupant comfort. To compensate for bending stresses originated in the skins by the non-circular shape under pressurization, additional unidirectional tape plies might need to be added in the fuselage hoop direction. Another compensation factor could be the use of asymmetric laminate lay-ups [24].

![Figure 2 - Cross-section](image2)

The two skin halves are secondarily bonded together with an edge band transition and a single strap butt joint at the fuselage centerline (Figure 3). A redundant bolted joint shall be used to meet fail-safe requirements.

![Figure 3 - Skins Joint Detail](image3)

The proposed energy absorbing floor structure implements the already described NASA concept of foam filled cellular beams construction. The basic structure of the cellular beams are closed cell PMI foam blocks that receive each one, braided fiber glass sleeves, and are assembled to a sandwich panel by fabric (carbon or Kevlar) facesheets. The concept is illustrated and described by Figure 4. Large panels can be easily manufactured, from which the beams can be cut according to their shape in the aircraft. The floor beams are co-bonded to the fuselage skin and pressure bulkhead.
1. Fiberglass applied over foam blocks

2. Reinforced foam blocks assemble to form a panel or beam

3. Beam cured and cut to size

4. Beams assembled to the floor structure

The floor beam is represented in Figure 2 with a 40mm thickness, but the optimum thickness and also the core density and facesheet laminates layup should be determined through a detailed crash simulation [25]. The available height is a compromise of occupant comfort, safety and aerodynamics (influenced by fuselage overall diameter). The current study is considering a height of 155mm for the inboard beam and 88mm for the outboard. The detailed crash simulation should also determine if these heights would be sufficient to absorb the FAA recommended impact conditions.

The traditional seat tracks are abandoned by the current concept, and the occupant seats shall be directly attached to metal fittings integrally mounted to the floor beams. As illustrated by Figure 5, the fittings are bonded to the foam core and wrapped by the fabric layers. The fitting has a shape that increases its bonding area to the core.

Not considered as part of the scope of the present study are the cabin door and escape hatches, which are areas that might also require additional details and reinforcements.

A complete and efficient evaluation, sizing and optimization of the crashworthiness features of the proposed fuselage concept including a correct material selection can be only performed by static and crash simulations using finite element methods. Acoustic behavior should also be considered in the optimization [27]. All these analyses should be part of the next phase of the project.

MANUFACTURING TECHNOLOGIES

Manufacturing process and tooling are the elements that control the success and cost of a composite component and it is therefore mandatory that they should be considered as an integral part of the design process. The basic idea is to reduce costs by conceiving highly integrated designs with less expensive raw materials and simple tooling concepts.

At the present, the processes based on prepreg technology method are the most used for the manufacture of high-quality aircraft composite components, since it provides a very high and reproducible component quality, while requiring a moderate investment of tool. The high component quality is attained by compacting and curing the prepreg (resin impregnated, continuous fiber products) in the autoclave under specified conditions. For some resin systems, vacuum bagging and oven curing are sometimes a
possible alternative to the expensive autoclave cycles. Relative simple tooling is required because only single-sided supporting tools are needed. The main disadvantages of the prepreg technology are the high material costs, due its elaborated preparation process, and the more complicated lay-up process, when compared to dry fiber material, since the applied resin film is already activated making it very difficult to handle.

The Resin Transfer Molding (RTM) process has become established in the past few years as an alternative to the prepreg technology. In the method, a cost-effective, non-impregnated fiber preform is placed in a massive mold to which a low-viscous resin system is injected under pressure. The considerably lower costs of the semi-finished products are advantageous here when the manufactured quantity warrants the investment costs for the vacuum-tight, temperature-adjustable and pressure-loaded molds. Since a compacting of the laminate in all directions is not possible in the massive mold, a reduction in the fiber content and in the quality of the laminate might be expected. When used with braided performs, RTM process can be the ideal for the manufacturing of profiles with composed cross-section.

VARTM (Vacuum Assisted Resin Transfer Molding) is an adaptation of the RTM process and is very cost-effective in manufacturing large structures. In this process a liquid resin is infused into the perform by pulling a vacuum on the mold tool. Also only single-sided tools are required and the resin is introduced to the preform with inlet tubes and a manifold system located on the outer surface of the preform. Vacuum pressure alone is used to compact the preform and as with any liquid-molding process, control of the resin flow front is necessary to assure that the preform is completely and uniformly infused with resin. High fiber volume fraction (70%) can be achieved by this process and therefore high structural performance is attainable in the part.

Taking advantage of the FAA approved shared material allowable database and all methodology behind it, currently the prepreg process, with vacuum bagging and oven curing, is the most adequate for the manufacturing of the sandwich parts of the proposed concept. For the near future however, the expansion of databases and certification policies covering specifically advanced material forms and processing are being expected, and the VARTM process will probably be the most cost effective manufacturing process.

For the skin sandwich panels specifically, if prepreg process is considered, a Nomex honeycomb core should be the best choice, since it would be the most weight effective. With VARTM process however, it might worth to explore the advantages of a PMI foam core.

For the floor structure, regardless of the manufacturing process, PMI foam core shall be used due to the extraordinary energy absorption characteristics of this material. Kevlar fabrics are currently also not covered by the shared databases, but could be the best alternative for the floor beams wrapping.

CONCLUSION

Advances in aircraft crashworthiness can be achieved by the development of crashworthy composite fuselage concepts that with extreme simplicity can overcome the traditional aluminum designs. The proposed fuselage section concept besides its added crashworthiness features represents a great potential for weight and manufacturing costs reduction. With the composite design, maximization of the internal space was possible and there is a great potential for internal noise level reduction. Additionally, taking advantage of FAA new policies and approved material allowable database a streamlined certification process can be expected. Taken as a whole, the proposed concept can represent a very strong market differential.

REFERENCES


