COMPOSITE AIRFRAMES - OPPORTUNITIES, OPTIONS AND ISSUES

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Abstract

Worldwide, both in the Civil and Military Aircraft Industry, there is an increasing usage of composites due to the inherent advantages they offer. However, even today, the total potential of composites has not been realized as the designers are still conservative. Also, cost has become a very important factor especially for civil aircraft. In order to realize the full potential of these materials, extensive research is being conducted in several areas that include design, newer, faster and cost effective approaches to manufacturing, better understanding of damage tolerance and associated failure theories, crashworthiness behavior and the like. Structural Health monitoring has progressed significantly and could play a major role in the reduction of maintenance costs and prevention of catastrophic failures. This paper makes an effort to address the options, challenges and issues that are confronting the composite industry today.

Introduction

Amidst the growing experience in design, development and familiarity with composite materials, the industry is vying for materials and processing technologies which are cost effective, maintenance free and which allow in-service monitoring. Innovation has been the key to the evolution of composite structures. This gives opportunities to researchers to explore the choice of materials, processing technologies, magnitude of cocuring, hybridizing with metals and integration of various sensors which eventually lead to reduced costs and promote greener technologies.

Nobel Prize winner Robert Solow (1956) said "About 88% of economic growth is created by innovation". This statement is as true today as it was 50 years back, and innovative technologies continue to drive the economic growth. The aerospace composite industry started in a small manner in the late 70's and has been continually making advances in composite technologies ever since. However, the emphasis on the usage of composites has changed over the course of the last 25 years. The previous efforts were mostly focused on structural weight reduction. Today, economical and ecological considerations are becoming increasingly important. Weight, manufacturing costs, fuel efficiency and other in-service parameters remain core driving factors, but sustainability and component recycling issues are also influencing current development strategies. Thus, modern aircraft design and manufacturing technologies take into account all direct and indirect aspects of operating aircraft.

Current aircraft programs are employing new materials, processes, structural concepts and better design philosophies. The adaptation of 'newness' renders composite design to rely on the development of new methods in design, testing and validation through the building block approach. Structural polymeric composite materials often exhibit different responses and failure mechanisms because of their in-homogeneity and anisotropy and this behavior is compounded by a multitude of toughened resins and improved fibers. However, this has not deterred the industry from employing composites in a large scale in on-going programs by comprehensively addressing their limitations. Structures like fuselage, interface fittings, landing gear lugs etc. have been realised and tested, areas where brittle composites were never considered as candidate materials. Worldwide research is going on in the field of crashworthiness, 3D reinforcements / 3D preforms, optimal fiber placement through fiber steering, fiber metal laminates, toughened resin systems, liquid composite moulding, resin film infusion etc.

Opportunities in Design

Design philosophies for composite structures have evolved over a period of time and the experience from service performance has played an important role. The consideration of fatigue in the design has evolved from the last couple of decades of service experience. Damage tolerance based on fracture mechanics approach evolved through service experience, has now become a way to design inspection programs. The service experience especially with newer materials can become an impediment since the direct application of experience gathered with previous materials may not be possible [1]. Researchers are looking at various means to monitor the health of structure and assess its safety. Now, structures are being integrated with a network of sensors to monitor their health during service life of the aircraft and intelligence is being incorporated in these systems to have both diagnostic and prognostic capabilities.

Laminated composites are inherently weak in their through-the-thickness properties with low interlaminar strength and fracture resistance. Such laminates are not suitable for applications where through-the-thickness stresses may exceed the tensile strength of the matrix or interface. Moreover, 2D laminates have poor impact damage resistance and low post-impact mechanical properties [2]. This is a major concern with composite aircraft structures where tools dropped during maintenance, hail impacts and runway debris impacts can cause damages. These damages result in the degradation of in-plane mechanical properties under loads. The degradation of normalized tensile and compressive strengths of a typical carbon-epoxy composite is shown in Fig.1 and it can be observed that the post-impact strength of laminates drops rapidly with increasing impact energy [3,4]. In order to maintain the residual strength after damage, composite parts are generally over designed using knock-down factors which are often conservative. This approach has a direct bearing on the cost and weight.

Considerable improvements in damage resistance can be achieved using both the constituents of composite viz., tougher resin or reinforcement in z-direction. Chemical and rubber toughening of resins and interleaving using tough thermoplastic film have been tried. The major drawbacks with these methods are the high cost of toughened resins and interleaving processes and difficulties in the proper distribution of fine rubber particles in the matrix. Furthermore, the tougher resins provide only moderate improvements to impact damage resistance and the usage in large practical composite structures is still being studied. Substantial improvement to through-the-thickness properties is possible by using 3D composites made using a variety of textile processes viz., weaving, knitting, braiding, stitching, tufting, Z-pinning etc. The manufacturing of preform using a particular process depends on the end application. For certain applications, it may be necessary to combine a number of the textile processes in order to obtain a product that satisfies the requirements of cost, performance, production rate, manufacturing risk, etc [2].

Studies carried out on the impact damage tolerance of 3D woven composites show that the amount of impact damage caused to 3D woven composites is less than 2D laminates with the same fiber volume content. Fig.2 shows the effect of increasing impact energy on the amount of delamination damage experienced by 3D carbon epoxy composites reinforced with an orthogonal or interlocked woven structure [5]. It can be seen from Fig.2 that the amount of impact damage experienced by the 3D woven composites is much lower than the 2D laminate. The outstanding damage resistance of 3D woven composites is due to their high delamination resistance. The improved resistance can be directly related to the fracture toughness for mode I [6] and mode II [7] between 2D and 3D laminates as shown in Fig.3.

The interlaminar toughening mechanisms like tufting and z pinning hinder the spread of delaminations from the impact site by the crack bridging of the z-fibers. The superior impact damage resistance of 3D woven composites usually results in higher post-impact mechanical properties compared to 2D laminates as shown in Fig.4 [8].

This technology is important, especially for cocured wing box structures wherein ribs and spars are subjected to out of plane loads due to fuel pressure and the integrity of joints is a major concern for designers. The concerned joint is the T joint between the skin and stiffener, the strength of which can limit the use of cocured structures in such applications. The effective way of preventing debonding between skin and stiffener in such cases is to introduce a mechanical link connecting skin and stiffener flange from top to bottom [9]. This reinforcement can be stitching /tufting for dry fabric preforms, or "Z-pins" for prepregs as shown in Fig.5 a and b respectively [10].

Results of T-pull tests on these specimens are shown in Fig.6 a and b respectively. Graphs clearly indicate the delayed initiation of the crack along with the increased T-pull strength [10]. The magnitude of increase of load carrying capacity depends on the density of z pins/ tufts. Studies on the impact on the T joints with different patterns of reinforcements showed that the z reinforcement helped in enhancing the residual T pull strength after impact as shown in Fig.7 [11]. Furthermore, studies on the fatigue performance have showed a significant increase in the fatigue life when z pinning / tufting has been used. Scaling up this technology for implementing on large cocured structures will, however, be a major challenge.

The textile processes like stitching, weaving, braiding, knitting etc. have the potential to significantly reduce the cost of manufacturing and produce structures that have improved mechanical performance in critical design cases such as impact. However, the process of placing of fibers in z direction can cause some damage to the reinforcement yarns and thus degrade the in plane performance of the final composite to some extent. The reduction in in-plane static strength properties may be offset by the improvement in damage tolerance properties which may hold the key. The processes used to design and produce the preforms for a specific application are not yet fully mature. Future developments should focus on accuracy, reproducibility, reliability and automation.

Researchers are working on innovative and highly promising production methods that may substantially improve the properties of composites and a truly optimized structure. In the current generation of composites, the fibers are positioned in straight lines. This kind of alignment is well suited where the load path is straight and does not deviate much along the length of the structure. There may be instances where the load path could be changing and current technologies cater to this by placing additional layers in that direction which adds to the weight and complications in fabrication like ply drop off. The straight line positioning of fibers will be non-optimal in terms of the load direction and the resulting design would be heavy. Research is being conducted on improving the alignment of the fibers by placing the fibers in curved paths. This technology has the potential to design a truly optimized structure, thereby allowing more efficient loading of the aircraft. A lug was taken as a case study to verify whether fiber alignment could be improved. This required the determination of the fiber vector field using stress analysis around the lug. Fig.8a shows the lug with fibers aligned using active fiber steering technique [12]. Research has also shown that buckling loads of composite panels can be improved significantly by allowing the laminate stiffness to vary locally [13]. Fig 8b shows the varying fiber orientation thereby changing laminate stiffness over the panel area. The active fiber steering technique looks promising to design regions around cut outs in a wing panel or a fuselage window panel.

The challenge that the optimized structures have to face is the compliance with damage tolerance philosophy. This approach allows the safe operation of a structure containing an allowable size of flaw/damage. Damage tolerance evaluation of a primary aircraft structure under typical load and environmental spectra expected in service, is intended to ensure, that should fatigue, intrinsic/discrete damage, manufacturing flaws/defects, or severe accidental damage occur within the operational life of the aircraft, the structure will withstand reasonable loads without failure or excessive structural deformation until the damage is detected.

The primary concerns in a metal structure relate to tension crack growth and corrosion, whereas other damages such as delaminations and fiber breakage resulting from impact events and environmental degradation are more of a concern in polymer matrix composites. In addition, composites have unique damage sensitivities for compression and shear loading, as well as tension. Within the analyses and certification process of the composite structures, care has to be taken not only to design and test the undamaged structure, but also to assess the influence of damage on strength and durability of the structure.

Airworthiness Requirements

The damage tolerance design procedures for civil/commercial aircrafts are addressed in Federal Aviation Regulations (FAR) 23.573, 25.571, 27.571, 29.571 and Joint Airworthiness Requirements (JAR) 25.571 [14]. Advisory Circular 20-107A and ACJ 25.603 provide means of compliance with the regulations concerning composite structures [15]. Advisory Circular AC 25.571-1 provides means of compliance with provision of FAR Part 25 dealing with damage tolerance and fatigue life [16]. The current aeronautical requirements for composite aircraft structures with damage can be briefly summarized as [17].

- Structure containing damages/defects that are not detectable during manufacturing inspections and service inspections must withstand ultimate load and not hinder operation of the aircraft for its entire lifetime (Fig.9).
- Structure containing damages that are detectable during maintenance inspections must withstand a once per lifetime load, which is applied following repeated service loads occurring during an inspection interval.
- All damages that lower strength below ultimate load must be repaired when found.

- Structure damaged from an in-flight, discrete source (lightning strike, bird-strike, uncontained rotor/fan burst etc.) that is evident to the crew must withstand loads that are consistent with continued safe flight.
- Any damage that is repaired must withstand ultimate load.

Static and fatigue tests are usually conducted during design, development and validation to show that composite structures satisfy certification requirements.

Composite aircraft parts can be damaged during manufacturing, assembly and service. A particular concern in composites is low velocity impacts that can cause significant damage that may not be clearly visible. Sources of such impact damage include falling tools and equipment, runway debris, hail, birds, and collision with other airplanes or ground vehicles. Airplanes can also be damaged by high velocity impacts from discrete source events such as (a) bird strikes, (b) parts of rotating machinery that fail in turbofan engines and penetrate the engine containment system, the aircraft skin, and supporting structure etc. Typical defects that occur in the manufacturing stage include improper cure or processing, improper machining, mishandling, improper drilling, tool drops, contamination, substandard material, inadequate tooling and mislocation of holes or details. The most common in-service damage is due to an impact event. Sources of in-service damages include hailstones, runway debris, ground vehicles, lightning strike, tool drops, bird strikes, turbine blade separation, fire, wear, hygrothermal cycling, repeated loads and chemical exposure. All structures designed need to address these issues.

Certification of Composite Aircraft Structures

The airworthiness certification of composite aircraft structures typically follow a building block approach (Fig.10) where a systematic combination of various tests and analyses are used to minimize the risk at different design stages [17]. Typically, hundreds to thousands of tests are conducted at the coupon and elements levels (Fig.11) in order to obtain material properties, develop design allowables, characterize environmental effects and study durability. These tests also help to develop and validate analytical and numerical models developed to show compliance of sub-components and components to airworthiness regulations.

Compliance through analysis has gained much significance in recent years since it gives ample scope for time and cost savings compared to traditional component level tests which tend to be elaborate, expensive and time-consuming. A typical test sequence for airworthiness certification of a composite aircraft structure is shown in Table-1 [18].

Crashworthiness Issues Applicable to Civil Aircraft

The fundamental issue regarding crashworthiness is ensuring that occupants of the aircraft fuselage survive the impact of a crash. This can be achieved by ensuring that the fuselage of an aircraft is designed such that enough energy absorption occurs in the structure and the seats and lower accelerations are transferred to the occupants. If specified acceleration levels are exceeded, the result would be forces that cause injuries and fatalities. These are classified by loads on various parts of the human body, for each of which criteria have been defined. These definitions are provided for example in the regulatory clause FAR 25.562 clause used widely by civil aircraft manufacturers. The requirements, for ensuring that accelerations transferred to the seat are not exceeding allowable limits, are that adequate energy absorption devices are available in the fuselage of a civil aircraft and the structural integrity is also maintained such that the occupants are contained in a survival space during the impact.

There have been considerable amount of studies on metal fuselage structures where the effect of the cabin size to the impact pulses encountered have been studied from commuter aircraft fuselages to large aircraft. These studies and analysis of actual aircraft crashes have led to the view that metal structures are adequate for crashworthiness in large aircraft, if designed to ensure that the regulatory requirements are taken into account. As discussed in studies at NASA Langley *(Fasnella and Jackson, Impact Testing and Simulation of a Crashworthy Composite Fuselage Section with Energy-Absorbing Seats and Dummies, 2002)* [19], to meet these objectives, an aircraft or rotorcraft fuselage must be designed for high stiffness and strength to prevent structural collapse during a crash. Yet, the fuselage design must not be so stiff that it transmits or amplifies high impact loads to the occupants. Ideally, the design should contain some crushable elements to help limit the loads transmitted to the occupant to survivable or non-injurious levels. Tests have been carried out at full scale level, component level, scaled fuselage level and at the feature level. In many cases, the building block ap-

Table-1 : Typical Test Sequence of a Test Box Towards FAR Certification [18]

Apply small damages (BVID)	
1	60% Design Limit Loads (DLL) Conditions - Strain Survey
2	Repeated Loads (Fatigue Spectrum) - 1 Lifetime (including 1.15 load enhancement factor to account for potential data scatter in CFRP S-N curves)
3	60% DLL Conditions - Strain Survey
4	Repeated Loads (Fatigue Spectrum) - 1 Lifetime (including 1.15 load enhancement factor to account for potential data scatter in CFRP S-N curves)
5	Design limit strain survey
6	Design ultimate loads
Apply visible damages (introduced after the end of the two lifetimes of repeated loads)	
7	Repeated Loads (Fatigue Spectrum) including 1.15 load enhancement factor - 2 Inspection Intervals
8	Fail safe (limit) loads : 100% DLL Conditions
Apply element damages	
9	"Get home" loads : Approximately 70% DLL Conditions - "Continued Safe Flight" Load Levels
Repair visible and element damages	
10	Design Ultimate Loads Conditions
11	Load to Destruction
Note : Small damages are defined as those which are at the threshold of detestability or barely visible impact damage (BVID). Visible damages were defined as damages readily detectable during the scheduled inspection plan, and included dents and small cuts to the skin panels and spars. Element damages were defined as complete or partial failure of one or more structural units.	

proach has been followed. Fig.12 shows a full scale test on an ATR commuter aircraft [20 and 21].

In metal fuselage structures, the predominant energy absorbing process is by plastic deformation. For composite fuselage structures, the issue is more complex, as energy absorption could occur by a variety of complex processes, including crushing (which is the primary means of energy absorption), fibre breakage, matrix cracking, delamination etc. For the Boeing 787, which is predominantly a composite airplane, much research and technology development has taken place. FAA has classified this as a special condition, in comparison to metal structures and reviewed the practices. (FAA14 CFR Part 25: [Docket No. NM368] Special Conditions No. 25-07-05-SC), where it is noted:

The 787 fuselage will be fabricated with carbon fibre reinforced plastic (CFRP) semi-monocoque construction, consisting of skins with co-cured longitudinal stringers and mechanically fastened circumferential frames. This is a novel and unusual design feature for a large transport category airplane certificated under 14 CFR part 25.

Structures fabricated from CFRP may behave differently than metallic structures because of differences in material ductility, stiffness, failure modes, and energy absorption characteristics. Therefore, impact response characteristics of the 787 must be evaluated to ensure that its survivable crashworthiness characteristics provide approximately the same level of safety as those of a similarly sized airplane fabricated from traditionally used metallic materials (Ref. Fig.13).

The crashworthiness of composite structures has been studied for a number of years [19, 20 and 21]. In NASA for example, we see studies on scaled models and drop tests that examine the efficiency of using foam in the energy absorbing subfloor. These studies have had both an experimental and finite element component. Fig.14

shows tests and analysis carried out on a scaled model which had Rohacell foam as an energy absorber [19]. In this work, there has also been good correlation between analytical results and experiments using simple models for the crushing and composite failure modes. In NLR [22], there have been studies on sub floors that use composites extensively, including sine wave beams as energy absorbers shown in Fig.15.

While, there have been considerable caution in using composites for crashworthiness, especially GFRP based on the complex failure modes involved, the opportunities available from weight reduction and long term maintenance cost reduction is appealing. At, National Aerospace Laboratories (NAL) there is a serious interest in studying energy absorption behavior of composites and work has commenced in this regard.

Opportunities in Manufacturing

The aerospace industry's shift from metal to composite as a building material might be increasing structural efficiency and weight savings, but it is also introducing a tough challenge on reducing costs. The US currently spends around $1 billion a year on aerospace composites research and is providing the lead to the successful transition to carbon fiber composite structures. Emphasis in the US appears to be on high levels of automation for existing component designs and assembly methods, as opposed to integrated component designs and novel processes which might reduce assembly costs. Efficient production of major structural parts is currently one of the major issues that companies worldwide are looking at and increasingly elaborate and complex methods for the laying-up of carbon fiber reinforced plastics (CFRPs) are being looked into. From the traditional assembly by hand before curing, there is now a shift to gantry-type and large, finely-controlled fiber placement machines. This automation revolution is likely to be the defining factor in the expansion of carbon fiber products into the mass market. However, the critical issue is to try and achieve the results currently being achieved at the high end of the industry much more affordably, and in this respect the technology is still very much in its infancy.

Over decades, the aerospace industry has gained experience in developing and evaluating manufacturing processes for advanced fiber reinforced composite materials and structures. Considerable knowledge has been acquired in the development of advanced composites via the prepreg/autoclave moulding route. NAL has played a key role in the development of cocured composite structures for Light Combat Aircraft and Light Transport Aircraft programs using prepreg materials and autoclave technology. The principal advantages of this technology are the elimination of stress concentration due to holes, elimination of expensive fasteners, reduced assembly time and associated costs.

However, in recent years, the focus of the industry has been on out of autoclave processing to improve process time whilst maintaining quality and reducing manufacturing costs. A key focus is on the use of new materials for the dual processing techniques of dry fiber pre-forming and low cost resin infusion. Dry fiber preforming avoids the high cost of working with prepreg materials, as the dry fiber can be preformed to near net component shape and the final composite component is then produced by infusing the dry preform with a matrix resin. Advanced fiber preforming techniques also offer a highly promising approach for improving the impact performance of composite structures as well as reducing the cost of their manufacture.

Bombardier Aerospace at Belfast has been making efforts to reduce the total number of C Series wing components and simplify the assembly process of its composite wing development programme, which will increase the operating efficiency and reduce the environmental footprint. The primary structural components, which are the integrally stiffened upper and lower skin panels and the spars, will be manufactured using Bombardier's Resin Transfer Infusion (RTI) process. RTI is a hybrid of Resin Transfer Moulding (RTM) and autoclave processing and is a patented process developed solely by the Belfast operation. It involves the use of dry fabrics to create the structure and then injecting resin into the structure once it is placed in the autoclave. This results in material savings and reduced cycle times.

NAL has developed its own innovative process called Vacuum Enhanced Resin Infusion Technology (VERITy) (under patent) and is developing the composite wing for its civil aircraft SARAS using this process. This process has demonstrated the potential of LCM by employing several supplementing technologies like tooling, automatic resin infusion system and flow sensors. Using this process, a completely cocured bottom skin with spars, ribs and stringers has been successfully developed (Fig.16) resulting in significant cost reduction (@ 20%) over the conventional prepreg process.

Typical problems stem from these manufacturing processes, such as uneven resin distribution. Resin starved areas can lead to porosity whereas too much resin can lead to internal stresses. It is also necessary to consider the effects of damage once the part is made, particularly in handling over the lifecycle of the aircraft. Barely Visible Impact Damage (BVID) is one of the important issues that need to be addressed. Machining and drilling can also often cause delaminations. Many NDT companies are looking at instruments that can perform rapid NDE. The key benefits that these new NDE technologies provide are reliable and quick solutions to the problem. One of the important aspects the NDE companies are looking at is removing the need for couplant and immersion techniques.

Another area of research which is now gathering pace is thermoplastic composites. The promise of a greener environment is driving technologists to look at these materials even though their processing costs are higher. One of the promising applications is in the leading edge of aircraft. PPS, PEEK and other thermoplastics are being examined. The damage tolerance capability of thermoplastic composites is nearly an order of magnitude greater than the conventional thermoset composites being used today. However the complex processing combined with higher cost and poor creep resistance has deterred their growth. Serious attempts are being made to overcome these limitations and this is evident from the fact that Airbus has already introduced a glass/ PPS leading edge on one of its commercial aircraft.

Concluding Remarks

Relevance of composite technology in future lies in the ever continuing introduction of better materials in terms of higher strength, fatigue allowable, lower weight, efficient processes and ability to integrate innovative structural concepts. The issues associated with the environment and green technologies will also have a bearing on composites. While, composites have made a major contribution, its understanding, unlike metals has been at a much higher granular level. Major work in micro-mechanics and damage mechanics could increase the use of composites even more. Also, integration of adaptive structural concepts will take place in composites. The adaptation of these novel technologies by composite industry would require the development of new methods in testing, validation through extensive analysis and certification. Numerous processes like autoclave moulding, out of autoclave moulding, resin film infusion etc. in conjunction with variations like cocured stiffeners, secondary bonded stiffeners, stitched stiffeners etc. are possible. These structures will have different characteristics with regard to damage resistance, damage growth and damage tolerance. Moreover, these structures display different modes of failure and failure mechanisms. In view of this, the damage tolerant design of composite structures will be a major challenge for ensuring the structural safety. The realistic assessment of practical damage scenarios is very important which should involve the definition of threat, initial damage detestability and damage growth. The type of inspection must be part of both design process and design criteria. Notwithstanding the above, the often occurring surprises and lack of service experience with new materials have made it necessary to look for structural health monitoring to assure safe structure in the future The fact that composites, unlike metals is a layered, non-isotropic material is now providing opportunities for sensing and control, both of which will enable better performance of aerospace vehicles.

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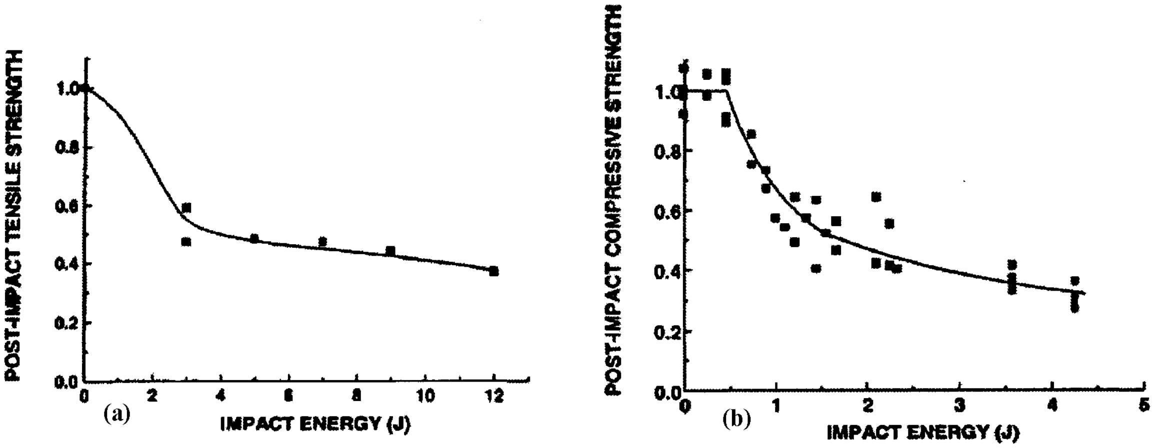


Fig.1 Effect of Impact Energy on the (a) Residual Tensile Strength [3] and (b) Residual Compressive Strength of 2D Carbon/epoxy Laminate [4]. The Post-impact Strength Values are Normalized to the Strength of the Laminate without Impact Damage

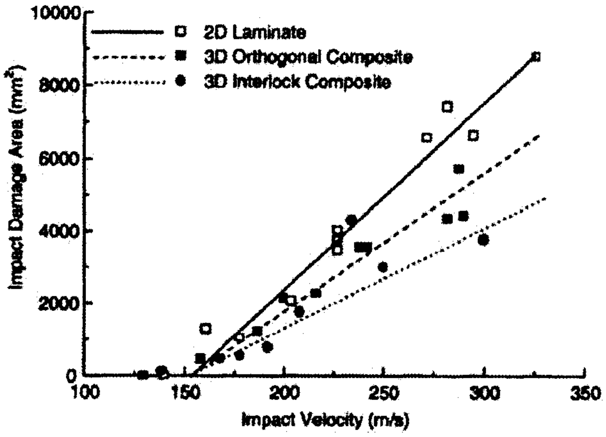


Fig.2 Effect of Impact Velocity on the Amount of Delamination Damage to 2D and 3D Woven Composites [5]

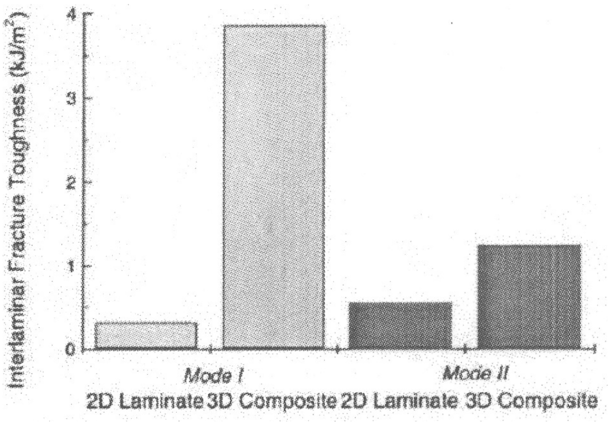


Fig.3 Comparison of the Delamination Resistance of 2D and 3D Composites for Mode I [6] and II [7] Loading

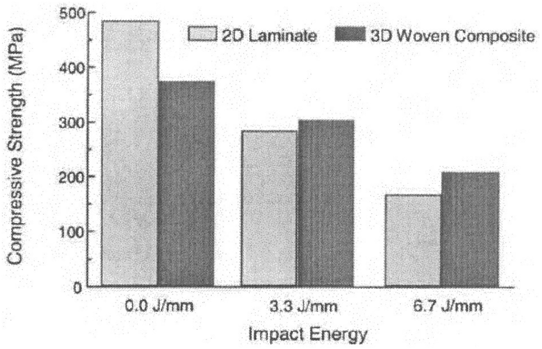


Fig.4 Effect of Impact Energy on the Compressive Strength of 2D and 3D Woven Composites [8]

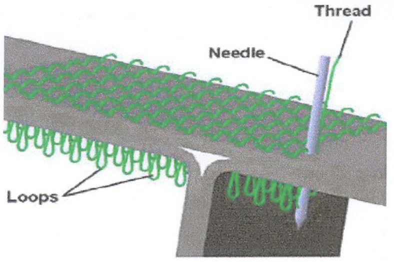


Fig.5a Tufting of T Joints in Dry Preforms [10]

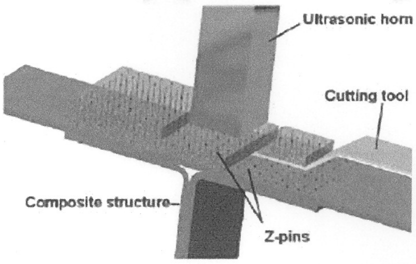


Fig.5b Z-pinning of T Joints in Prepregs [10]

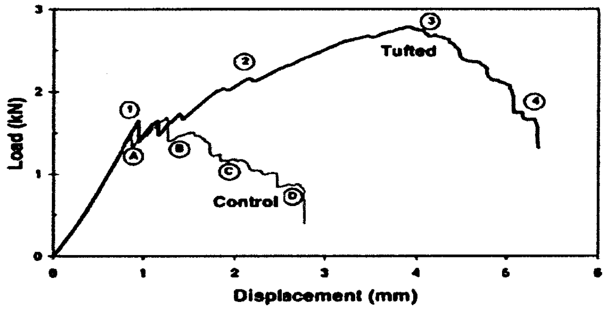


Fig.6a T Pull Tests in Tufted Preforms [10]

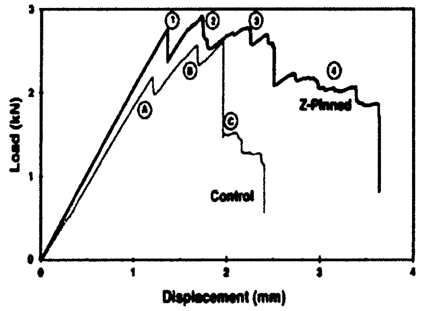
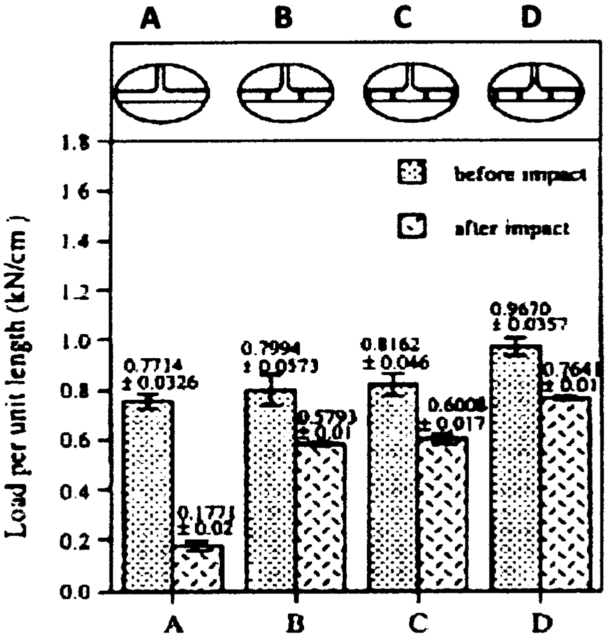


Fig.6b T Pull Tests in Z Pinned Prepregs [10]



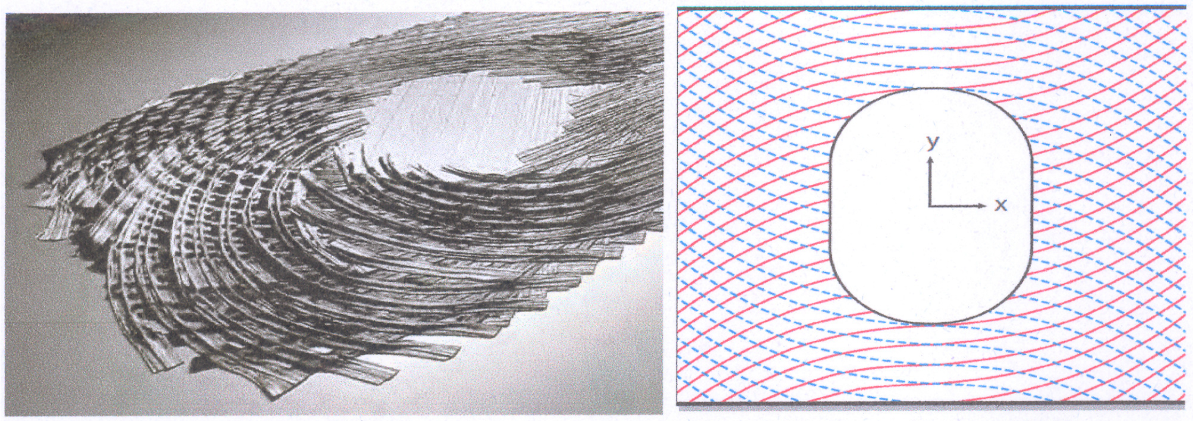
A: Unstitched

B: One stitch on both sides of fillet between skin and flange

C: Two stitches on both sides of fillet between skin and flange

D: Two stitches on both sides of fillet between skin and flange

Fig.7 T Pull Strengths Before and After Impact with 7.35 J for Different Stitch Configurations [11]



a) Around a Lug [12]

b) Around a panel [13]

Fig.8 Active Fiber Steering

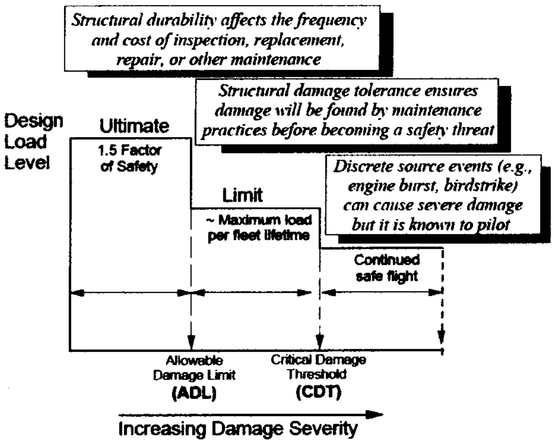


Fig.9 Design Load Level for Different Damages Sizes

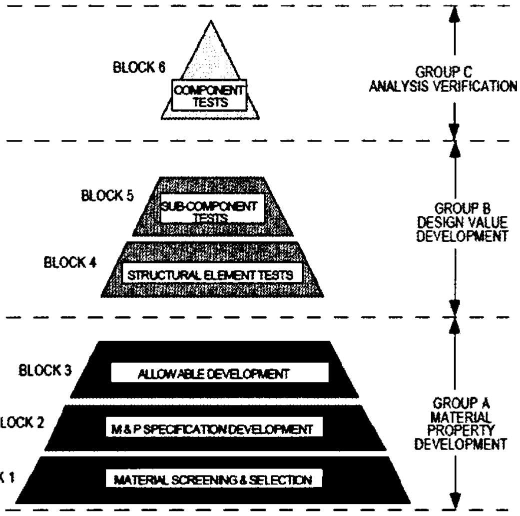


Fig.10 Building Block Approach Towards Certification

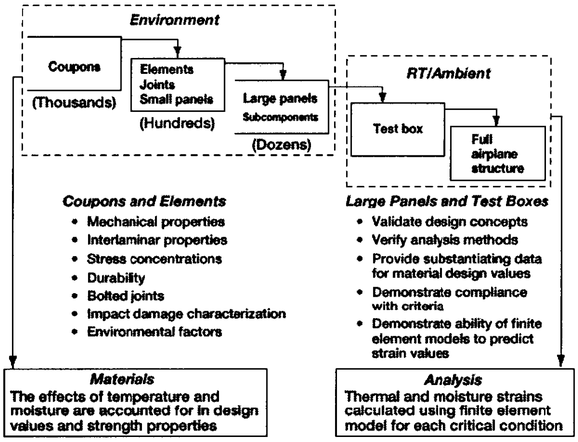


Fig.11 Details of the Building Block Approach

Fig.12 Drop Test on a Full Scale Commuter Aircraft

Fig.13 Drop Tests being Conducted on a Boeing 787 Fuselage

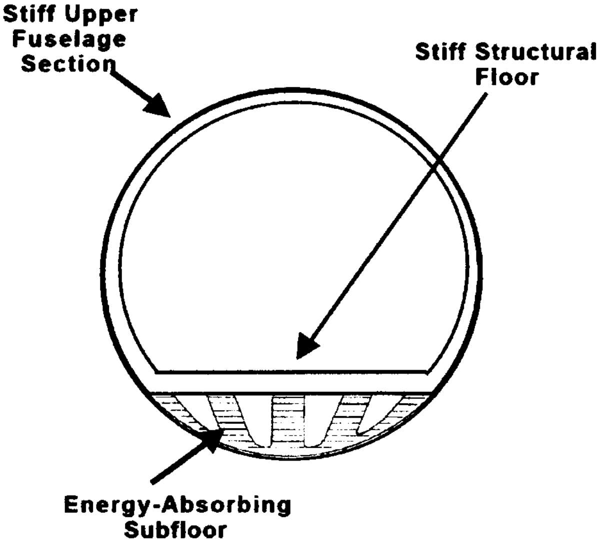


Fig.14 Energy Absorbing Concepts Using Foam

Fig.15 Energy Absorbing Subfloor Using Sine Wave Beam Concepts

Fig.16 Resin Infused Wing Skin with Spars, Ribs, Stringers and Gussets for CSIR-NAL's SARAS Aircraft