ABSTRACT

There is significant amount of analysis and validation performed during certification to demonstrate the airworthiness of aircraft structure. This ensure the safe operation of the aircraft under standard operating environments and load condition that the aircraft is intend to operate throughout its design service goal. There is a growing concern of terrorist attempt to sabotage aircraft with the use of improvised explosive devices (IED), which can be placed in either cabin or cargo hold area to sabotage aircraft and cause catastrophic failure. Although there are significant amount of guidance materials and data are available for dynamic events such bird strike and crash scenarios, limited amount of data and guidance available for threats due to IEDs. The IED explosion in PAN AM Flight 103 punched a 20-inch wide hole on the left side of the fuselage, which caused separation of the nose of the aircraft within three seconds. Although the explosion was in the forward cargo hold, the large pressure differential between cabin and the atmosphere magnified the damage propagation causing destruction of the aircraft and 270 fatalities. After bombing of PAN AM Flight 103 on December 21, 1988 and French Airline UTA Flight 772 in September 1989, aviation sectors including regulatory agencies, law-enforcement and intelligence agencies, and airlines led to several key aviation security initiatives such as the Aviation Security Improvement Act of 1990 to improve the aviation security. Furthermore, several research initiatives were executed to investigate the vulnerability of then state of the art aircraft structures (primarily metal) and the means to mitigate the risks of a catastrophic failure caused by terrorist act using IED such as what was used during the attack of PAN AM Flight 103. Results from the studies spurred investigation of aircraft-based blast mitigation applications such as blast-resistant baggage containers and protective cargo hold liners. Furthermore, several intrinsic measures such as localized reinforcement of skin and frames, improved stringer attachments to fuselage and strategic placement of system equipment were studied to reduce the vulnerability of catastrophic structural failure. The studies have shown the terrorist attacks against civil transport aircraft is a significant threat, i.e., loss rate of 1 per 10^7 flights worldwide averaged over 30 years. Therefore, the structural improvements augment the added security measures following the Aviation Security Act of 1990 to mitigate the vulnerability of civil aircraft to IED attacks. The primary goal of this investigation is to assess the vulnerability of modern composite fuselage structures to a damage caused by an internal explosion from an improvised explosive device. The applications of composite materials in modern commercial aircraft are evaluated through a literature survey of composite structural details. Composite panels will be fabricated to simulate fuselage details for blast testing. First phase of the research will focus on unstiffened flat panels for model validation. Then, curved stiffened panels will be fabricated for blast testing.
1.0 Introduction

In the early 1970s, composite materials were introduced to airframe structures to increase the performance and life of the airframe. Reduction in weight results in better fuel economy and decreases direct operating cost for the end users. Researchers and aircraft manufacturers recognized that although composite applications reduces operational cost through weight savings (consequently better fuel economy), the initial acquisition cost was significant due to high manufacturing cost for composite structures. In 1977, the National Aeronautics and Space Administration (NASA) Advanced Composite Structures Program introduced the use of composites in primary structures in commercial aircraft using advanced design and manufacturing concepts to produce low-cost composite structures, i.e., the Boeing 737 horizontal stabilizer with sandwich construction that was developed under NASA Aircraft Energy Efficiency (ACEE) program (Figure 1) [1,2]. In 1983, Airbus introduced composite rudder for A300 and A310, followed by horizontal and vertical stabilizer including control surfaces of A320 (Figure 2). In addition to weight savings and better fuel economy than that of the metallic counter parts, composite materials coupled with advanced design and manufacturing technologies resulted in a significant reduction in part count. However, the higher acquisition cost and the stringent certification requirements hinder the large-scale use of composites in primary structures. In 1994, the Advanced General Aviation Transport Experiments (AGATE) consortium led by NASA and supported by the Federal Aviation Administration (FAA), industry, and academia, revitalized composite material product development in general aviation, thereby cost-effective composite airframe structures. Modern improved composite materials and matured processes have encouraged commercial aircraft companies to increase the use of composites in primary and secondary structures. Driven by the demand for fuel-efficient, light-weight, and high-stiffness structures that have fatigue durability and corrosion resistance, the Boeing 787 Dreamliner is designed with more than 50 percent of composite structures by weight, marking a striking milestone in composite usage in commercial aviation. Meanwhile, the Airbus A350 commercial airplane is being designed with a similar percentage of composite materials in its structure. Figure 2 shows the use of composites in several commercial aircraft applications.

Composite structural certification requires rigorous analysis validated by experiments. Analysis alone is generally not considered adequate for substantiation of composite structural designs. Instead, the "building-block approach" to design development testing is used in conjunction with analysis (Figure 3). This approach is often considered essential to the qualification/certification of composite structures due to the sensitivity of composites to out-of-plane loads, the multiplicity of composite failure modes and the lack of standard analytical methods. The building-block approach is also used to establish environmental compensation values applied to full-scale tests at room-temperature ambient environment, as it is often impractical to conduct these tests under the actual moisture and temperature environment. Although significant amount of analysis and experiments are performed during certification of an aircraft structure including crash analysis, blast performance of structures subjected to an internal explosion is not investigated in detail as a part of the certification requirements. Structural analyses of fuselage under blast scenarios require high strain rate sensitive constitutive response of materials as well as validated dynamic models that require significant analysis details and costly experimental validations. Publically available analysis and test data for such incidents is rare or proprietary. Furthermore, guidance for analysis and validation of such an experiment is rare.
Figure 1. Boeing 737 composite horizontal stabilizer [3].
The goal of this proposed research would be to identify and compile detailed information on composite material types, properties and configurations, and structure configurations (stringers, frames, bonded/riveted joints, etc.) in passenger cabin and cargo hold areas of modern composite aircraft. Secondary goal is to gather dynamic material properties for composite materials used in modern aircraft fuselage (i.e., CFRP due to high strain rate) to support the modeling and testing efforts. Investigation of structural responses for dynamic events such bird strike and crashworthiness are part of the building-blocks of analysis validated by testing approach. Such efforts require significant amount of supporting data such as strain rate sensitive material data as well as considerable amount of computational capacity. Experiments even at small scale can be costly and require unconventional test apparatus. Simulation of blast testing requires more complex analysis tools/methods and specialized test facilities. Data gathered in this investigation will provide information on current “state of the art” composite applications that will benefit large-scale experiments focusing the structural response of composite fuselage for internal explosion.

Figure 2. Composite materials applications in commercial aircraft.
2.0 Background

There is significant amount of analysis and validation performed during certification to demonstrate the airworthiness of aircraft structure. This ensure the safe operation of the aircraft under standard operating environments and load condition that the aircraft is intended to operate throughout its design service goal. There is a growing concern of terrorist attempt to sabotage aircraft with the use of improvised explosive devices (IED), which can be placed in either cabin or cargo hold area to sabotage aircraft and cause catastrophic failure. Although there are significant amount of guidance materials and data are available for dynamic events such bird strike and crash scenarios, limited amount of data and guidance available for threats due to IEDs. The IED explosion in PAN AM Flight 103 punched a 20-inch wide hole on the left side of the fuselage, which caused separation of the nose of the aircraft within three seconds [4] (Figure 4). Although the explosion was in the aircraft cargo hold, the large pressure differential between cabin and the atmosphere magnified the damage propagation causing destruction of aircraft and 270 fatalities (including 11 fatalities on the ground due to impacting of disintegrated aircraft structural segments). After bombing of PAN AM Flight 103 on December 21, 1988 and French Airline UTA Flight 772 in September 1989, aviation sectors including regulatory agencies, law-enforcement and intelligence agencies, and airlines led to several key aviation security initiatives such as the Aviation Security Improvement Act of 1990 to improve the aviation security. Furthermore, several research initiatives were executed to investigate the vulnerability of then state of the art aircraft structures (primarily metal) and the means to mitigate the risks of a catastrophic failure caused by terrorist act using IED such as what was used during the attack of PAN AM
Flight 103. Results from the studies spurred investigation of aircraft-based blast mitigation applications such as blast-resistant baggage containers and protective cargo hold liners [5]. Furthermore, several intrinsic measures such as localized reinforcement of skin and frames, improved stringer attachments to fuselage and strategic placement of system equipment were proposed to reduce the vulnerability of catastrophic structural collapse. As can be seen in Figure 5, the studies have shown the terrorist attacks against civil transport aircraft is a significant threat, i.e., loss rate of 1 per $10^7$ flights worldwide averaged over 30 years [5]. Therefore, the structural improvements augment the added security measures following the Aviation Security Act of 1990 to mitigate the vulnerability of civil aircraft to IED attacks.

Figure 4. The wreckage of PAN AM Flight 103 (Boeing 747).

Figure 5. Comparison IED incidents between 1970 and 1993 to airframe failures (non-sabotage) and incidents involving aircraft being shot/forced down [5].

The research conducted following PAN AM Flight 103 on the vulnerability of then state of the art structures were primarily on metallic structures. Figure 2 shows the increase use of composite materials in commercial aircraft primary structures. With the increased use of composite materials in commercial...
aircraft fuselage, i.e., Airbus A380, Boeing 787, and Airbus 350, there is a need to investigate the structural response of modern composite structures to an IED blast to ensure, at least, the same level of structural capacity is present in composite fuselage structures as metallic fuselage. Although there has been significant amount of recent research work done on the dynamic response of composite structure, i.e., bird strike, crash scenarios, etc., relatively limited amount of work has been done to investigate the blast response of composite aircraft structures.

Furthermore, the analyses of composite structures subjected dynamic loads, i.e., crash loads, require the determination of rate-sensitive dynamic mechanical properties. Development of standard quasi-static mechanical properties for composite materials is well understood and standardized. However, generating high strain-rate mechanical properties is complex, i.e., experimental difficulties associated with inertial effects, high rate test machines and data acquisition systems, lack of standardized test protocols, etc., and publically available databases are scarce [6,7].

3.0 Technical Approach

The use of advanced composite materials in aircraft structures has increased since early applications of secondary structures such as fairing, floor beams and interiors to primary structures such as fuselage, wing, empennage, etc. Figure 6 shows the evolution of advanced composite material application in Boeing commercial airplanes. As seen in Figure 7, commercial applications of composites lagged behind military applications due to general conservatism and lack of past experience as well as the cost of manufacturing. Aircraft applications must consider advanced materials, innovative design and manufacturing technologies, structural health management, and operational cost. Safety is the key priority in aircraft applications and therefore, structural design, manufacturing, and product life cycle cost is considered in analysis to produce cost effective and airworthy structures. The primary goal of this investigation is to assess the vulnerability of modern composite fuselage structures to a damage caused by an internal explosion from an improvised explosive device.

Research program consisted of two phases:

**Phase 1** – Literature survey and identify and compile detailed information on composite material types, properties and configurations, and structure configurations (stringers, frames, bonded/riveted joints, etc.) in passenger cabin and cargo hold areas of modern composite aircraft. The building-block test data including high strain rate response of material and structural details will be collected for modern composite structures. Lessons learned from blast testing of structural details, including tests performed on metallic structures, will be investigated.

**Phase 2** – Design and fabrication of representative composite panels for blast testing based on the information gathered in Phase 1. Applicability of past safety features that have been in place for years and found to be effective for metallic structures will be investigated for composites structures.
The applications of composite materials in modern commercial aircraft (only Boeing 787, Airbus A380 and A350 will be considered) are evaluated through a literature survey of composite structural details. A comprehensive list of composite structural details of modern aircraft as shown in Figure 8 will be generated. The evolution of advanced materials, design philosophy, and manufacturing technologies will be investigated. The modifications to current aircraft to prevent catastrophic event such as PAN AM Flight 103 will be studied. Design data such as material/design allowables, high rate mechanical properties, environmental effects, etc. that can be used for modeling and simulation of blast testing will be gathered. The building-block approach is a vital mechanism to understand the structural performance and mitigate risks by developing database to support aircraft structural certification. Vast amount of environmental test data is gathered during development and certification programs. Although majority of such design-specific data is proprietary, publically available databases such as NCAMP that contained environmental data for advanced materials used in current applications will be gathered. In addition to environmental data, publically available rate sensitive mechanical properties as well as physical and thermal properties will be documented. Such details will be beneficial for further studies, i.e., design, analysis and fabrication of representative aircraft structure for full-scale blast test evaluation.

Once the design and fabrication information are gathered, a representative test panels will be fabricated for blast testing. Phase 2 of this research will primarily focus on fabricating test panels of a modern composite fuselage construction as shown in Figure 9. Design and fabrication details such as geometry, dimension, materials, fabrication, etc. will be finalized by the research team from FAA, WSU/NIAR, and industry partners upon completion of Phase 2.
Figure 7. Commercial and military composite applications by structural weight [8].

Figure 8. Boeing 787 composite fuselage construction.
Figure 9. Composite hat-stiffened fuselage test panel.

4.0 References


