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THE COMING PARADIGM-SHIFT IN MAINTENANCE: FROM METALS TO COMPOSITES

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The purpose of this study is to examine the current maintenance practices of airline operators in the detection and repair of damage to composite structures, with the aim of learning lessons that will be applicable to the maintenance of future advanced composite airplanes. A process map was created to capture the events and activities that occur from the moment a damage event occurs, through damage detection, assessment and repair. The study is identifying areas where operational risks may negatively impact the process, where personnel are required to make judgments in the absence of procedural guidance, and areas where future tools or techniques may be of assistance.

The continued airworthiness of aging aircraft is the subject of a research project within the NASA Aviation Safety Program. The aging of aircraft structures is not necessarily an inevitable consequence of the passage of time, but is related to the accumulated effects of flight operations, exposure to environmental conditions, and events during ground handling and maintenance. For example the turnaround of an aircraft at the gate involves the coordinated movements of numerous vehicles and support equipment with the constant potential for contact with the aircraft. Most impacts will be inconsequential, but on occasion, an aircraft structure may sustain damage.

The principle of damage tolerance used in aircraft design ensures that aging-related structural damage can be detected and corrected before it presents a threat to the airworthiness of the aircraft (Goranson, 2007). For example, an awareness of the rate of crack propagation in various metal structures, combined with estimates of the probability of crack detection by an inspector, have allowed inspection schedules to be designed rationally to minimize the risk that an undetected crack will grow to a dangerous length between inspection intervals. From this example, it can be seen that the concept of damage tolerance, that is central to modern aircraft design, relies on two knowledge domains. The first domain is squarely within the field of engineering, specifically knowledge of materials and structures, and the conditions they are expected to encounter during their service life. The second domain is concerned with human performance, specifically the capability of maintenance and engineering personnel to detect, recognize, and rectify degraded conditions before such conditions become dangerous. The application of the damage tolerance concept requires the on-going collection and analysis of in-service data related to these two knowledge domains (Kim, Sheehy, & Lenhardt, 2006).

Aircraft structures have been fabricated from metals for over 70 years, and in that time, aircraft manufacturers and operators have accumulated experience in the design, maintenance, inspection and repair of metallic structures. The failure modes of metallic structures have been studied extensively, and parameters such as the rate of crack propagation can be estimated (Thompson, 2002). The human factors of inspection and damage analysis with metallic structures have also been widely studied (Drury, 1999) and the probability of detection can be estimated for cracks of various lengths under various viewing conditions (Ostrom & Wilhelmsen, 2008).

In line with wider industrial trends, the manufacturers of airline aircraft are now reducing the use of metals in aircraft construction and increasing the use of composite materials. A composite is a material composed of two or more ingredients that are combined at a macroscopic level, and are not soluble with each other (Kaw, 2006). For example a typical matrix composite material is made of woven carbon fibers set in an epoxy resin. Composites have been used in a wide range of products, including boats, consumer goods, military aircraft and advanced general aviation aircraft. Composites are used currently in a variety of structural and non-structural components in commercial airplanes. Examples range from basic fiberglass radomes, honeycomb core engine cowlings, lightweight winglets made of graphite-epoxy materials, and carbon fiber reinforced plastic (CFRP) materials comprising elevators, rudders, ailerons, and spoilers, up to the newest of the glass reinforced aluminum laminate (GLARE) technology utilized in fuselage skins in some aircraft. Composite materials provide advantages including weight savings, increased strength, resistance to corrosion, and aerodynamic efficiency. The next generation of airliners will be characterized by the increased use of composites in primary structures such as the fuselage, empennage, and wings.

Despite the promise and benefits that composite materials hold, they bring a new set of airworthiness issues. Although composites exhibit superior strength in many situations, composite failures can involve mechanisms very different from those of metals. For example, composites failures may involve delamination, fiber breakages, and fluid ingress. Compared to metallic structures, composite materials may also react differently to impacts or abuse, and may experience internal damage while showing little outward sign that damage has occurred. Fatigue cracks in a metallic structure will generally propagate over an extended time period, and the structure may retain much of its strength until an ultimate failure occurs. In contrast, some composite materials experience a sudden loss of strength when damaged.

As composite materials become increasingly important in the airline industry, it is necessary to understand the tasks that must be carried out by operational personnel to ensure the continued airworthiness of aircraft that include composite materials. Some tasks are likely to involve significant perceptual elements, for example, the detection of dents and delamination. Other tasks will largely involve decision-making and communication on matters such as the assessment of damage, and the subsequent repair action. On some occasions, social factors may come into play, for example, the willingness of personnel to report events where they may have caused damage to a composite structure, particularly when no visible damage is apparent. In contrast to trade skills such as welding, the field of composite fabrication and repair is characterized by a lack of standardization and the absence of consistent skill and knowledge requirements for technical personnel. However, as the aviation industry accumulates experience with composite materials, an increasing amount of regulatory standards and general guidance material is being produced by regulatory authorities, the military, and industry groups, notably the SAE Commercial Aircraft Composite Repair Committee (e.g. FAA, 1984; Department of Defense, 2002; Blohm, 2007).

Purpose of the Current Research

The purpose of the current research was to develop a methodology that can be used to examine the information sources, procedures, decisions, tools, expertise, and communication tasks relevant to the maintenance of composite materials on commercial aircraft. This methodology will then be used to help identify task elements that involve human performance-related risks. Such risks could include, but are not limited to; perceptual demands that exceed human capabilities, complex decisions that must be made in the absence of documented guidance, areas where task performance is reliant on expert judgment, situations where social factors such as a culture of blame could interfere with processes, and circumstances where there is a need for tools or technology not currently available. The methodology will be applied to the current state of the practice of managing aircraft composite damage in operations with the aim of identifying current operational risks as well as risks that may carry over to future advanced composite airplanes.

Development of the Methodology

Identifying the Broad Flow of Events

The first step was to identify the broad flow of events in the damage management process. Figure 1 shows five distinct types of events, beginning with events that present hazards to composite materials and moving in time order to ultimate damage mitigation, usually repair. Each stage is likely to involve a distinct population of operational personnel and specific human performance challenges.

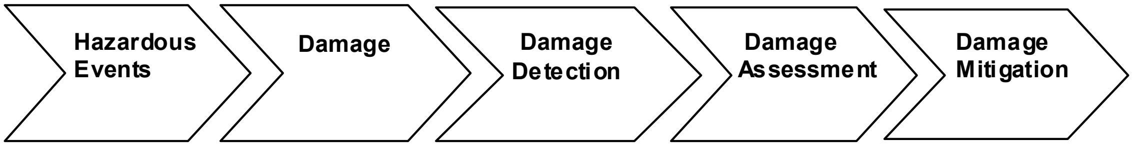

Figure 1. The flow of events in the damage management process.

Hazardous events. Hazardous events are defined as occurrences or conditions that have the potential to damage a composite structure. Hazardous events include bird strikes, in-flight exceedances such as flap over-speeds, maintenance errors such as dropped tools, ramp events, and weather phenomena. It is important to note that although a hazard may be a precursor to damage, a hazard does not necessarily lead to damage. The awareness that a hazard has occurred, however, is an important trigger that may lead to damage detection. The following report illustrates a maintenance-related hazard involving a composite panel on a Boeing 757-200. The incident is one of many that have been submitted to NASA's Aviation Safety Reporting System (ASRS). ASRS is a voluntary, confidential and non-punitive system that enables aviation personnel to report unsafe occurrences and hazardous situations.

> *I was performing an op Job Card on the #2 engine. This op includes an open cowling inspection and then an open up of certain borescope plugs. After the plugs had been installed, the cowlings were closed and some tools were left in the cold stream of the engine unintentionally. I did not realize the tools had been misplaced until after my weekend, which was 4 days later. …. After returning to work after 3 days off I was informed that damage had occurred to the #2 engine thrust reverser, composite panel, as result of the tools.* ASRS Report #463194

Ramp personnel such as baggage handlers and service vehicle drivers may observe hazards on the ramp, such as impacts involving vehicles, loading equipment or jetways. In some cases, the damage resulting from such events may not be clearly visible; as a result, the damage may remain undetected if the hazardous event is not reported.

It has been well established that various organizational factors can discourage the open reporting of incidents. Clearly, punishment of those who report errors or incidents actively discourages personnel from disclosing maintenance incidents. The potentially subtle nature of damage to advanced materials, such as barely visible impact damage or subsurface damage may create dilemmas for personnel who may have unintentionally created the hazard (i.e. dropping a tool) when there are no visible signs of damage and yet reporting the incident may lead to negative consequences for the worker (Boeing, 1994).

At present there are unanswered questions about the human involvement in the detection of, and response to, the events that can damage composite structures. The current research project is considering a range of human factor questions related to these hazardous events, including:

- *Information*: What are the sources of hazardous events? During what stage of operations do they occur, e.g. in-flight, ground handling, maintenance? What signs indicate that a hazardous event has occurred?
- *Procedures*: Are there appropriate and standardized procedures to guide the organization's response to a hazardous event report?
- *Decisions*: What influences whether a person will decide to report a hazardous event, particularly when the event involves a human action?
- *Tools*: Are some events detected via technologies such as on-board quick access recorders?
- *Expertise*: What operational personnel are in a position to detect hazardous events?
- *Communication*: How is information on hazardous events collected, documented and communicated to enable damage detection, assessment and mitigation to occur?

Damage Types. An important distinction can be made between the hazardous event as *cause* and the damage as *consequence*. Delamination, dents, and fiber breakages are examples of the consequential damage that may occur following a hazardous event. Delamination is a failure mode in which layers of the composite matrix separate, with significant loss of mechanical toughness. Common causes of delamination are repeated cyclical stresses and impact events. For example, in 1997, an Airbus A300 experienced an in-flight incident in which the pilot used excessive rudder inputs to steady the plane, imposing high lateral loads on the tail of the aircraft. The aircraft landed safely, and a preliminary visual inspection found no evidence that damage had occurred to the tail fin. In 2001, in response to an accident involving another A300, all A300-600 tail fins that had previously experienced high loads were required to go through ultra sound inspection. Severe delamination damage was found in one of the lugs that attach the vertical stabilizer to the fuselage of the A300 that had been involved in the 1997 incident (NTSB, 2004).

Damage Detection. There are three principal types of inspections during which damage may be detected. The first type is the scheduled inspection performed by maintenance personnel during transit checks, daily checks, and "letter checks" (A, B, C & D). Such checks typically include inspections of known problem areas where damage may occur. Most of these inspections are carried out visually. The pre-flight pilot walk-around can also be classed as a scheduled inspection. The second type of inspection is the "non-directed" inspection, or serendipitous discovery. This is where the technician or inspector was not engaged in actively searching for the damage at the time of its discovery. For example, Goranson (2007) notes that many cracks in aircraft metallic structures are discovered during non-directed inspections. Many cases of non-directed damage discovery have been reported to NASA's Aviation Safety Reporting System (ASRS), as illustrated by the following example:

> *After removing vertical stabilizer panel (on Airbus A320) to inspect wiring harnesses per our job card, we noticed small cracks propagating from 2 hi-lok fasteners on the front spar next to the transverse load fittings. We informed inspection and they made a write-up. At this time, engineering is still trying to decide what to do. There is no type of NDT [Non Destructive Testing] that will tell us how deep the cracks are…. The reporter said the spar is of composite construction and no non-destructive testing methods or instruments are presently available and no repair processes are in the structural repair manual.* ASRS Report #613739.

The third type of inspection is the conditional inspection. These are initiated in response to a reported event that presents a hazard to the aircraft. Current maintenance procedures include conditional inspections triggered by events such as lightning strikes and heavy landings.

Scheduled and conditional inspections may involve one of three levels of inspection, either general visual, detailed, or special detailed (Kinnison, 2004). General visual inspections are unaided inspections (except for basic support equipment such as ladders and work stands) and are used to detect obvious damage. Detailed inspection involves intense visual inspection, sometimes with the use of lenses or mirrors. Areas may be cleaned in preparation for inspection. Currently 80-90% of inspections of composite structures are visual and that is unlikely to change significantly in the near future (Waite, 2007). Lastly, special detailed inspections are intense examinations of an area involving the use of special non-destructive testing (NDT) techniques. These techniques involve the use of technologies such as ultrasonics, thermography, and x-ray.

Human factor questions related to detection of damage in composites include:

- *Information sources*: How evident are the signs of damage? What signs of damage does the inspector look for?
- *Procedures*: What techniques are currently being applied to the detection of composite damage? What proportion of damage is detected through scheduled inspections/non-directed inspections/conditional inspections?
- *Decisions*: What decisions need to be made during inspections?
- *Tools*: What technologies are used to assist in damage detection and how are they used?
- *Expertise*: What skills, knowledge and training are required to perform inspections?
- *Communication*: How is information on detected damage collected, documented and communicated to enable damage assessment and mitigation to occur?

Damage Assessment. Once damage has been detected, it is necessary to assess its extent, evaluate its implications for airworthiness, and decide on a repair action. Most damage assessment decisions are guided by documentation such as the structural repair manual or maintenance manual. In other cases, engineering staff apply technical knowledge and expert judgment to design a tailored response, particularly when the damaged area is one that rarely sustains damage, or where no standard response is available. In complex cases, the engineering response may require consultation with the original equipment manufacturer.

Human factor questions related to the assessment of damage to composite materials include:

- *Information sources*: What factors are taken into account in decision making?
- *Procedures*: What guidance material is available to assist assessment?
- *Decisions*: What major decisions need to be made about damage assessment? Who is involved in these decisions? To what extent is damage classification a matter of judgment?

- *Tools*: How are NDT technologies used in damage assessment? How is the need for NDT determined?
- *Expertise*: What expertise is required to assess damage?
- *Communication*: How is information on damage assessment collected, documented and communicated to enable damage mitigation to occur?

Damage Mitigation. Damage mitigation is the final step of the process. Mitigation may take the form of a temporary repair such as speed tape, a permanent repair, or the replacement of the damaged component. Composite repairs can require specialized skills and careful attention to conditions such as correct storage of perishable materials, pressure, temperature and curing time. The conduct of a successful composite repair appears to be heavily reliant on accurate human performance, adequate training and appropriate standards and procedures. Deviations from prescribed process can significantly impact the strength of a composite repair (Tomblin, et al., 2007). However the focus of the current study was on the events leading up to the repair activities, rather than the specific activities involved in carrying out the repair.

Development of a Process Map and Interview Protocol

In order to identify the operational risks and human challenges associated with the maintenance of composite structures, a series of site visits are being made to aircraft operators, and interviews are being conducted with personnel who are Subject Matter Experts (SMEs) in the inspection and maintenance of composites. SMEs are drawn from throughout the organization, including those who may observe hazardous events, (including pilots, ramp workers, and maintenance personnel), those who perform scheduled inspections, and engineering personnel involved in damage assessment decision-making.

A process map was developed as a data collection tool to capture the general progression from damage-causing events through damage repair. The structure of the process map ensures that all areas of the operational process are covered during site visits and interviews. The process map includes three potential paths to damage discovery, which are in line with the three types of inspections; scheduled, non-directed and conditional. The process follows a “funnel” pattern, where the early stages can involve a broad range of potential hazard events, as well as many professional and employment groups, from maintenance technicians, to pilots to ramp workers. For example a pilot conducting a walk-around, a professional engineer dealing with a non-standard repair, and the driver of a catering truck who has just bumped an aircraft, will each have a unique contribution to make to the safety of composite materials, but they have their own responsibilities, priorities, and different information needs. As the process continues, and damage is identified and assessed, the process “funnels” down to a narrow range of participants with specialized skill sets and specific knowledge of composite materials.

Following a short introductory discussion, the SME is asked to recall a specific incident involving composite damage that was discovered via one of the three potential detection paths. The incident is then used as a focus for questions as the SME is prompted to identify the people involved at each stage of the process, the tasks they performed, the decisions they made, as well as the information sources, documents, tools, and communication needs at each stage.

Site visits and interviews conducted to this point have enabled the process flow map to be refined to focus on areas of operational risk. It became apparent that personnel tended to have very localized knowledge, in that they could describe their part in the process, but did not necessarily have a good awareness of parts of the process in which they were not directly involved. Therefore the interview protocol was modified to target sections of the process flow according to the roles and expertise of the SME.

Conclusion

The increasing use of composite materials in commercial airline aircraft necessitates an improved understanding of the human involvement in their maintenance. Not only are composite structures significantly different to the metallic structures they are replacing, but the human factors involved in maintaining composite materials may also be significantly different. The lessons learned in the maintenance of existing composite structures on current aircraft are of great potential value as airline manufacturers increase their use of composite materials. The process flow model being developed as part of this study may be the first time that the processes involved in composite materials maintenance has been mapped with a view to identifying the human performance demands of the process and potential operational risks.

We have yet to see how the management of damage in future composite structures will differ from the current processes and practices used for metallic structures and current composites. However, the systematic mapping of current processes, and the gathering of the experiences of operators, will make it possible to identify parts of the existing processes that have the potential to present uncontrolled human performance-related risks, and will thereby predict issues that may arise in the detection, prediction and mitigation of damage in future composite structures. An enhanced understanding of human-related risks may help to inform the development of future technologies, practices, and guidance material, ensuring that the advantages of advanced composite materials are not undermined by uncontrolled process risks.

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