STRUCTURAL HEALTH MONITORING FOR ADVANCED COMPOSITE STRUCTURES

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Abstract

The use of Structural Health Monitoring (SHM) is a key to achieving technological leaps in the design and operation of engineering structures. Composite materials incorporating SHM systems enable the design and manufacture of tailored smart structures. This paper focuses on their application to aircraft as a means of highlighting the issues that face SHM in composite structures, including those in the maritime, oil and gas, civil infrastructure and other industries. Incorporation of SHM has the potential to reduce through-life costs by the adoption of Condition Based Maintenance and to reduce operating costs by the design of more structurally efficient aircraft. The paper addresses issues involved in the design, certification, manufacture and through life support of such structures. Critical areas of development have been identified to enable the implementation of SHM in future composite aircraft structures.

1 Introduction

In a future more akin to science fiction, a technological leap is being heralded in the design and operation of major engineering structures. Through the development of smart-structures technology, high-value assets such as aircraft and civil infrastructure will become “intelligent”, having the capability to detect when they have become damaged and analyse the effect of this damage on their performance well before the human operator is aware of any problem. The future in creating and operating engineering structures will be increasingly shaped by our ability to monitor them in a fashion more analogous to medical science than traditional engineering.

The smart-structures technology that is currently emerging into the commercial arena foreshadows a revolution in the structural design, manufacturing and maintenance of engineering structures. In particular, aircraft structures have always been at the forefront of innovation and a great effort is taking place to develop the systems to implement these technologies into reliable and effective SHM systems. In parallel with these developments, fibre reinforced polymer (FRP) composites are being increasingly used in aircraft structures. On the Airbus A380 FRP composites account for about 25% of the structural weight and on the Boeing 787 Dreamliner they account for about 50% of the structural weight [1]. By contrast, the Boeing 747 comprises 17%. Thirty-five percent of the structural weight of the F-35 Joint Strike Fighter will be FRP compared to 16% for the F/A-18 and 26% for the AV-Harrier II [1,2].

Because of the high cost of carbon fibre, early use of carbon fibre composite was restricted to applications such as aerospace where there was a high cost benefit in weight saving. With the rapid reduction of the cost of carbon fibre over the past decades (see Figure 1), the use of carbon fibre composites has become cost effective in other structural applications, particularly where the self weight of the structure is a major component of the operating load.

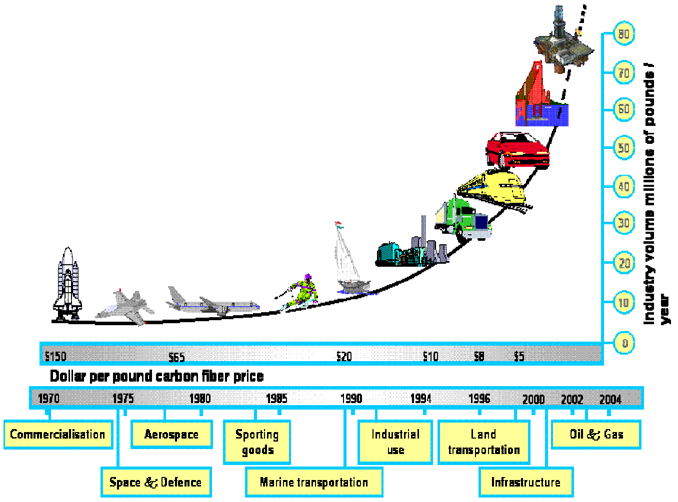

Fig. 1: Consumption of raw materials per industry sector. From [4]

Major aircraft manufacturers, both civil and military are committed to the introduction of SHM into future aircraft, particularly in composite structures, in order to exploit the commercial benefits of this technology [3]. It is feasible that SHM technology applied to aircraft will be prevalent in the next decade, and the experience and reliance on SHM may revolutionise the design of aircraft composite structures in the future. Loads monitoring in aircraft structures is common, where such data are used to manage aircraft utilisation and maintenance and advanced sensor technologies have been implemented. However, SHM, which monitors the health of the structure, has been installed in only experimental applications.

Advanced sensor technologies have been applied to ship structures for loads monitoring. In particular optical fibre sensors have been installed for this purpose in the Norwegian composite naval vessel HNoMS Skjøld [5,6] and in the carbon fibre reinforced polymer mast of a British-built yacht “Smart” [7]. However, the extension to SHM systems is currently only in the research phase. In other industries, the status is similar for the implementation of advanced sensor technologies for monitoring composite structures.

This paper examines the issues raised for future aircraft with the advent of Structural Health Monitoring (SHM) technology and specifically for the ongoing use of composite materials in aircraft. The suitability and limitations of various SHM systems is discussed in the context of their applicability to composite aircraft structures and to the transfer of this technology to other composite structures.

2 Structural Health Monitoring

SHM systems have the potential to continually monitor the health of a structure through strategically located sensors coupled with monitoring technology enabling remote interrogation of the sensors.

The essential ingredients of a SHM system include the following:

- Remote interrogation;
- Reliability;
- Durability;
- Capability to detect significant events such as impact or other overloads;
- Data integration in operational system;
- Diagnostic capability for damage;
- Prognostic capability.

2.1 Benefits of SHM

Within the global aerospace market the need to strengthen competitiveness whilst improving safety and security has become a crucial concern to aircraft manufacturers and operators. These concerns are not limited to the aerospace industry; however, the drive for SHM of composite structures is strongest in the aerospace industry. The implementation of SHM to aircraft and other composite structures, can help attain market competitiveness and to provide substantial benefits in the following areas.

- More efficient and effective maintenance procedures with substantially reduced down-time.
- Substantial time savings to inspect structures which are in difficult to access positions or in remote locations.
- Occupational health and safety benefits in accessing structures which are in hazardous locations.
- Structural health monitoring systems with reliable diagnostic and prognostic capabilities can provide the operator of the facility with information as to possible safe further operation subsequent to a mishap.
- Improved design efficiencies through the availability of continual monitoring, which will allow more conservative designs.

Worldwide, aircraft maintenance incurs staggering costs. In 2002 the nine major US airlines spent US$5.32 billion on maintenance alone [43].

Additionally it has been estimated that human error in maintenance activity contributes to approximately 15% of all aircraft accidents. The application of reliable SHM technology would result in the capability to remotely monitor the physical condition of components, reducing the costly requirement for aircraft downtime for component disassembly and inspection. This capability also opens the potential to move away from traditional “Time Based Maintenance” to “Condition Based Maintenance”. Thus aircraft structural maintenance can be optimally planned given the actual condition of the aircraft components and not controlled primarily by flight hours irrespective of component condition. These considerations apply equally to other applications such as, ships, offshore structures, oil gas and water pipelines, bridges and other civil infrastructure.

There are many occasions where, during routine maintenance, inspections are required of components which are buried in the structure and are difficult to access. Often substantial downtime of the facility results from disassembly to access and inspect such components. In many cases it is impossible to access certain areas and consequently considerable additional cost is incurred to ensure an ultraconservative design in recognition of the inability to access the component. Access to underwater structures and those which are in remote and inhospitable locations, for example in the case of pipelines, will also add considerably to maintenance and down time cost. SHM systems with remote access will facilitate such inspections and hence reduce costs and down-time.

SHM with remote sensing capabilities can provide substantial benefit and mitigate occupational health and safety issues where inspections are required in circumstance where the inspector is exposed to danger. For example, inside chemical or fuel tanks, in the proximity of hazardous materials, underwater, at heights or underground.

Structural health monitoring systems with reliable diagnostic and prognostic capabilities can provide the operator of the facility with information as to possible safe further operation subsequent to a mishap. For example, in the event of a collision of a ship with a foreign body, it is often not possible to ascertain if there is invisible damage to the hull which degrades its structural performance to a critical level. SHM systems will provide the captain with the information required to make the decision as to continue or abort the mission. In the absence of a SHM system the mission would necessarily be aborted.

A longer-term benefit has the potential to dramatically change future design and operation of aircraft and other major infrastructure. This is the optimised design of composite structures incorporating SHM systems. Many composite structures, particularly aircraft are currently over-designed due to the requirement for safe operation with undetected damage. With reliable monitoring of the structural condition some of the over-design can be removed and this will lead to reduced aircraft weight, new design concepts and increased performance. Some of the issues involving design of aircraft structures incorporating SHM are discussed in Section 5 below.

With operating costs, weight and performance being such crucial aspects of an aircraft’s competitiveness, opportunities offered by SHM become increasingly more important for aircraft structures. The application of SHM technology to other composite infrastructure will lead to similar benefits.

3 SHM Strategies

3.1 Monitoring Systems

There are a variety of approaches that can be used to monitor the health of composite structures and an increasing number of commercial systems are now available. Following are the three most common systems.

- Strain based SHM systems measure the strain distribution of the structure subject to operational loads via electrical resistive strain gauges or more commonly, optical fibre sensors. Any damage in the structure causes a change in the strain distribution which may be detected by the system.
- Vibration based systems rely on detecting changes in the vibration response of a structure to identify damage. Accelerometers, piezoelectric sensors or optical fibre sensors may be used to detect the vibration response.
- Sensor breakage is used as the basis for SHM in some systems. For example, the Comparative Vacuum Monitoring System relies on cracks in the structure breaching microscopic pressurised galleries in sensors attached to the structure. Similarly some systems rely on the fracture of embedded optical fibres to indicate and locate damage in composite structures.

3.1.1 Strain based systems

The strain of a structure under load can be readily measured and tracked over time. The presence of damage alters the local strain distribution due to the changing load path. To evaluate the structural condition, the strain in a composite structure subject to operational loads can be monitored in real-time with the use of sensors such as electrical resistance strain gauges, fibre optic sensors and piezoelectric transducers (Figures 2 and 3). This approach is generally more suited to the monitoring of known structural "hotspots" due to the localised nature of damage-induced strain anomalies. Fibre optic sensors are particularly suitable for the health monitoring of large structures such as pipelines because multiple sensors can be attached to a single fibre for distributed sensing over long distances [8]. The small size of fibre optic sensors (< 250 micron in diameter) imposes negligible intrusion into the host structure and allows fast interrogation with minimal wiring requirements.

Fig 2: Example of optical fibre sensor used for SHM

3.1.2 Vibration based systems

Vibration based systems are generally global in that the state of the whole structure is monitored by its vibration signature, consequently, damage anywhere in the structure may, in principle, be determined [9].

Stress wave techniques, of which there are two main forms (passive and active), are also a common approach to SHM. Acoustic emission monitoring is the passive approach in which acoustic signals generated through matrix cracking, fibre breakage or delamination are detected and analysed to determine the type, severity and location of damage. Active approaches (acousto-ultrasonics) generate stress waves from a source that can interact with damage, causing wave reflection and scattering. Through analysis of the wave changes, information on structural damage can be ascertained. Both techniques generally use piezoelectric transducers and can require complex signal analysis to determine the details of structural damage. Such sensors require a power supply and extensive wiring which can add considerable weight and cause electromagnetic interference with aircraft systems. However, recent developments in optical fibre technology allow optical fibre sensors to be used as vibration monitors.

Other vibration based techniques [22] can also be used to identify damage within composite structures. Impedance techniques, dynamic structural response and random decrement method are all approaches which utilise the change in the vibrational characteristics of a structure when damage is present. This approach can be performed through externally applied excitation or through the excitation forces occurring in service. Again, significant signal analysis is a requirement for this approach, particularly with complex structures. These are global techniques which can detect damage remote from the sensors.

It is often difficult to excite the structure in order to determine its dynamic response, particularly if the structure is massive with high damping. SHM techniques which use environmental loading for the excitation of the structure present a distinct advantage.

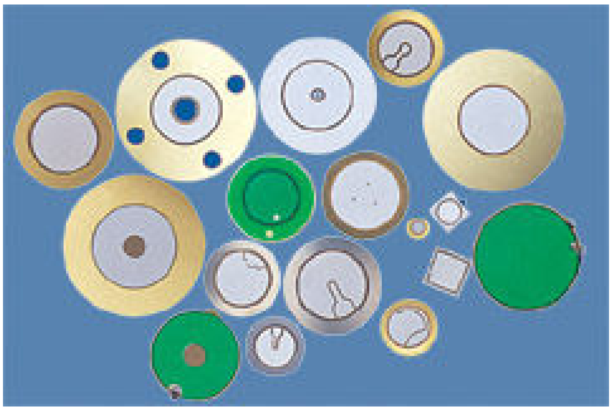

Fig 3: Example of piezoelectric transducers used for SHM

3.1.2 Sensor rupture

One technique in this category, Comparative Vacuum Monitoring [10,11] has achieved success in monitoring cracks in metal structures. The system relies on a patch incorporating fine galleries which are alternately evacuated. Any crack reaching the surface breaches these galleries and the resultant change in relative pressure can be detected. Research is currently being conducted to extend this technique to detect damage in composite structures.

Crack gauges, which rely on failure in electrical resistive strain gauges, are used to detect the length of opening cracks.

Failure in embedded optical fibres, which allows light to emerge from the fracture location, has been used as a method of indicating failure in composite structures [12].

3.2 Damage Diagnosis

An effective SHM system requires a robust scheme of damage diagnosis. This includes determination of the location and extent of the damage, establishing the nature of the damage, and assessment of the cause of the damage (not essential but desirable) [13]. The problem of damage diagnosis is one of pattern recognition. It can be expected that each damage state of a structure possesses a unique pattern pertaining to the mode of interrogation. Thus, given the collection of sensor measurements, the role of the diagnostic tool is to correlate them with a particular damage state. In order for SHM to become a core design concept and gain approval from certification authorities, it must be sensitive to critical damage mechanisms, such as impact and fatigue, and be capable of characterising the ensuing damage with an acceptable level of accuracy and reliability.

The strategies used to produce a damage diagnosis are highly dependent on the sensor arrangement and the mode of interrogation. Global sensing techniques, such as acousto-ultrasonics and modal assessment, rely on sophisticated data processing for the characterisation of damage. Often, a high-fidelity model of the structure is required, and the sensor responses to a large number of different damage scenarios are calculated. The measured signal is then compared to the knowledge database using artificial intelligence algorithms, such as neural networks to produce a final diagnosis [14,15]. There is limited capability to model complex structures with sufficient fidelity to detect changes due to damage, particularly when damping changes due to the damage are significant components of the changes in the signature.

It is attractive to consider another class of damage detection algorithms, based on statistical novelty detection [16] and which do not depend on the generation of a high fidelity model. The problem here is simply to identify from measured data whether a structure has deviated from the normal condition, i.e. if the data are novel. These approaches mostly involve modelling data based on their statistical properties and using this information to estimate whether a test sample comes from the same distribution. Statistical techniques can be applied to strain-based damage detection systems utilising fibre optic sensors [17]. The localised nature of this detection scheme means that the damage site can be easily determined by virtue of the sensor locations. The installation of large sensor arrays for wide area coverage can be efficiently achieved by utilising the excellent multiplexing capabilities of fibre optic sensors [8,17,18]. Similar techniques may be applied to systems which rely on vibration signatures to detect damage [19].

A diagnosis may change with time as more sensor data become available. One of the major benefits of SHM is its ability to detect damage at an early stage and to monitor its progression throughout the life of the structure, leading to improved diagnostic capabilities, more efficient repair strategies and ultimately more optimised structural designs. Continuing research efforts are needed towards the development of robust, commercial-grade damage diagnostic systems, which can be applied to a wide range of composite structures.

3.3 Prognosis

SHM systems are continuing to be developed which enable the determination of the location and extent of any structural damage and for the monitoring of loads and other operational parameters. For metal structures these data allow the confident prediction of the rate of damage progression and the estimation of the extent of the continuing safe life of the structure which enable maintenance and replacement planning. On the other hand the ability to predict damage progression and the residual life of composite structures is not well established. Composite structures are designed on the basis that any damage, which is not readily apparent, will not grow under the design loads. However, the residual performance capability of such structures is still of great interest. The capability of structural health prognosis is essential for a SHM system and it constitutes the highest level of a comprehensive SHM system [20].

Structural health prognosis requires intimate knowledge of the mechanical properties of the construction materials, including strength, stiffness, fracture toughness, and fatigue characteristics. Accurate information on the structural loading and boundary conditions are also required. The modelling of damage evolution and residual strength entails numerical tools such as stress analysis, crack growth models, and finite element modelling. Unlike damage diagnosis, which possesses a certain degree of universality in terms of its application, structural health prognostics is highly specific to the target structure and necessitates the creation of high-fidelity numerical models. Consideration must also be given to the effect of damage on related structural response beyond its immediate vicinity.

Perhaps for this reason, the majority of activities in the field of structural health monitoring has been devoted to the development and application of sensing technologies (i.e. diagnostic tools), rather than prognostic capabilities. Instead, the realm of structural health prognostics has been left largely to structural mechanists outside of the SHM community. It is important to note that without prognostic capabilities, little use can be made of the information from a damage diagnosis, however accurate it is.

Traditional structural health prognostics for metal structures, such as damage tolerance and fatigue life predictions, are obtained based on assumed structural flaws, regardless of whether they actually occur in service (i.e. the prognosis is made before the diagnosis). Consequently, a large degree of conservatism is incorporated into structural designs due to these uncertainties. The availability of effective damage detection capabilities using smart sensor technologies offers new opportunities for structural health prognostics. Instead of assumed flaws, actual detected damage characteristics can be used in the prognostic models for accurate, real-time prediction of future trends. As for a diagnosis, a prognosis can be continually modified with time as the damage develops. A schematic of this integrated SHM approach is shown in Figure 4.

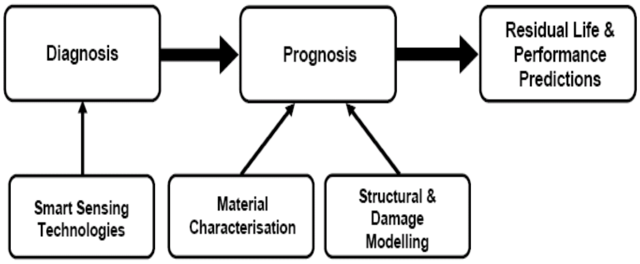

Fig 4: Integrated structural health monitoring approach

The combined diagnostic and prognostic capabilities through SHM can minimise the uncertainties associated with composite structures and lead to significantly more optimised designs with quantifiable increases in structural reliability. Alternate design philosophies, such as the probabilistic design methodology [21], over the traditional deterministic approach, may also work in tandem with SHM to further improve the optimisation of structural design and the management of risk.

4 Implementation

4.1 Manufacturing and Installation

From a manufacturing perspective, sensors can be installed after production onto the surface of the component, which minimises the disruption to the conventional manufacturing cycle. However, surface sensor installation requires the use of skilled technical labour at an additional cost to component production, and the use of adhesives and protective materials for the sensors and any necessary data cabling. All this adds to the cost and weight of the component and raises the issue of sensor durability during service as they are exposed to potential damage. In addition, for thick composite structures surface sensors may not be capable of accurately monitoring the precise locations of interest as they could be at some distance from the failure [22].

The production methods for composite structures offer the opportunity to build the sensors into the component itself. In doing so, the application of SHM sensors to the structure can be done as part of the component manufacture and not as a secondary operation. Embedding the sensor into the composite will also remove the need for adhesive and protective cladding as the sensor will be protected by the structure itself. Embedment also allows the placement of sensors at optimal locations for data measurement and can also provide more efficient data transfer paths through complex structures using embedded “cabling”. However, the effect of the sensors and ancillaries on the structural integrity of the composite must be addressed. The capability to embed sensors is an attractive advantage of composite materials. However, a process to incorporate sensors that is robust enough to suit conventional composite manufacturing methods has not yet been developed. The critical issue involves the ingress and egress of the sensor data lines.

In the example of fibre optic sensors, the physical size of the optical fibres makes them very suitable for embedding as they have a minimum effect on the surrounding material. However, with standard composite materials the resin will coat the optical fibre as it comes out of the composite, making it brittle to handle and thus requiring support [22]. The location at which the fibre comes out of the structure is also a concern, as all conventional composite components are generally trimmed along their edge. This makes the edge unsuitable for ingress or egress, however the alternative of coming out of the component surface is not ideal as this could significantly affect the surrounding composite material and would make component manufacture more difficult. Therefore a technical issue still to be resolved is the development of a robust process for sensor embedding and connection.

In addition to the initial manufacturing concerns, the inclusion of any system to an aircraft structure is a complex process, particularly if it involves the requirement for power and the need to transmit data within the plane (and possibly to external ground-stations). Any SHM technology should not conflict with systems currently used in aircraft and, ideally, should not add to the aircrafts' power and data handling burden. To overcome this concern many researchers are developing technology that can be self-powered and can communicate through wireless operation with other equipment [23]. Advancements such as this can help overcome barriers to the addition of any new system to an already "overcrowded" aircraft. Such systems would also find use in locations, such as underwater, where other power sources are difficult to access.

4.2 SHM System Reliability

It is essential that the SHM system provides reliable information. False positive indications are as damaging as false negatives to the integrity of the aircraft system. Reliability engineering techniques must be used to ensure an acceptable low probability of false negatives or positives. One advantage of SHM systems is that they provide continuous data and consequently reinterrogation will remove one-off errors. However, systematic errors must be avoided through robust system design.

4.3 Sensor Durability

A major issue for the development of robust SHM systems is concerns on the durability of sensors/actuators when subjected to severe load, temperature and environmental cycles. Having a clear understanding of the reliable sensor life is important for surface mounted sensors as the opportunity for replacement exists and could be incorporated within the maintenance of the smart structure. However, the issue of sensor and system durability is particularly critical when sensors are embedded within composite structures. In this scenario sensor replacement is not straightforward, so understanding and maximising the reliable life of the sensor is vital.

Work has been undertaken on sensor reliability. For the Fibre Bragg Grating (FBG) sensors used in optical systems, the inherent strength of the optical fibre can be reduced over time due to stress corrosion cracking in the presence of water [24]. Bare fibres are more susceptible than coated, but as many standard coating materials do not prevent water uptake, coated fibres also degrade due to corrosion. Elevated temperatures can also affect the gratings [25]. At room and slightly elevated temperatures the gratings appear to be stable, but when exposed to significantly higher temperatures the gratings start to decay (i.e. their reflectivity decreases) and at sufficiently high temperatures they disappear completely. Though for most optical fibres, significant grating decay will only occur at temperatures well over 100°C. Nevertheless, this illustrates the issue that SHM system performance may change over time.

Fatigue testing at room temperature of optical fibres to 4000 $\mu\varepsilon$, have shown [26] that in some cases fatigue cracks in the optical fibre occurred at about 50,000 cycles. This was attributed to the stripping of the coating from the fibre before writing the grating.

There is very little reported research on the durability of piezoelectric transducers.

The primary candidates for embeddable SHM sensors in composite structures (optical fibres and piezoelectric transducers) rely upon a good bond with the surrounding composite material to transfer strain fields. If this bond between the composite and sensor deteriorates, then the transmission of information will also be affected, potentially leading to a reduction in the capability of a sensor that may still be fully operational. The performance of embedded sensors and the interface between the sensor and the surrounding composite material, must be assessed under typical operational conditions. This may include mechanical and thermal fatigue, impact and environmental exposure to water and chemicals to which the system is exposed.

More investigation is required on the durability of these sensors and the factors affecting this durability.

4.4 Sensor Replacement

The system must have the capability for replacing components in a regular maintenance schedule or in the worst case if such components fail. This is particularly challenging for embedded sensors. A related issue is the restoration of the SHM system when structural repairs impinge on some of its elements.

A number of approaches could be taken to deal with damaged SHM systems. One option is to design and install the system with multiple redundancies, although that could increase the cost of the SHM system beyond practical considerations. Potentially a better approach would be to design the system so that the removal of any one (or more) sensors will not affect the performance of the remaining sensors in the system. Together with this, any replacement structure should also have embedded SHM capabilities to effectively replace the removed sensors. This could be designed to have the dual advantage of monitoring not only the basic composite structure, but also the integrity of any repair [27].

4.5 Remote Sensing and Data Acquisition

In many cases, sensors are located on structures in remote and inaccessible locations, often at great distances from any base station. There are major difficulties associated in data collection from these remote sensors and for delivering power to enable the operation of sensors and any associated data acquisition systems. The solutions to these problems will depend on the individual circumstances for each application. Solutions proposed for data acquisition range from the installation of extensive fibre optic cable systems, to interrogating local sensors via short range wireless by regular aerial patrols of infrastructure. For powering the systems, various energy harvesting options have been proposed including power generated by solar cells, through vibration of the system, or from the flow or pressure in pipelines. The level of development of such systems is immature and considerable research must be directed towards safe, cost effective and maintenance free systems to enhance the application of SHM. Of particular research interest are the various possibilities for energy harvesting.

4.6 Data Handling and Integration

The end-use of the SHM data must be integrated into the maintenance and operational system of the applicable platform or structure. The data presented to the end-user must be easily and reliably interpreted, and consequently, the vast amount of data that could be collected in a large plant must be refined through various levels and integrated with data from other sources. In the operation of the data acquisition, there is a trade-off between local processing and the transmission of small amounts of processed data and the acquisition of extensive data for remote processing. The installation and powering cost for local data processing must be weighed against the transmission costs of large quantities of data. These issues are currently being addressed for aircraft applications.

5 Design of Composite Aircraft with SHM

Due to susceptibility to damage and defects, particularly invisible impact damage, the full potential of composite materials is not exploited resulting in increased structural mass. Composites are typically designed to an allowable load of about 33% of the failure load of a pristine material, compared to 60% for a metal structure. Incorporation of SHM into composite structures has the potential to reduce many of these uncertainties and permit increased design allowables leading to lighter and more efficient structures. However, the scope of such improvements may have limitations. Reductions to structural sections may change failure modes and introduce issues involving buckling. Similarly, fatigue damage is currently not a serious consideration for composite structures because of the low design working strains, but may be a significant barrier to the use of increased of design allowables.

5.1 Design and Certification

The following discussion pertains to the certification of composite structures on large civil transport aircraft, and the basic principles may be transferred to other industries and applications. Design techniques and requirements for metallic aircraft structures, based on many years of development and operational experience, are well developed and accepted by the certification authorities. Certification requirements for composite structures are more conservative and are covered by guidelines issued by airworthiness bodies (e.g. [28-30]). The certification of composite structures is traditionally accomplished using a building block approach. Typically, tests on thousands of coupons, hundreds of elements, dozens of subcomponents lead up to one or two full scale tests [31,32]. These tests assess the properties of materials and sub-assemblies, durability, the effects of defects and damage and environmental factors. The larger tests validate design concepts and demonstrate compliance with certification criteria. The emphasis of the certification requirements is that non-detectable flaws are not critical to the structural integrity and do not grow to a critical size before the next inspection.

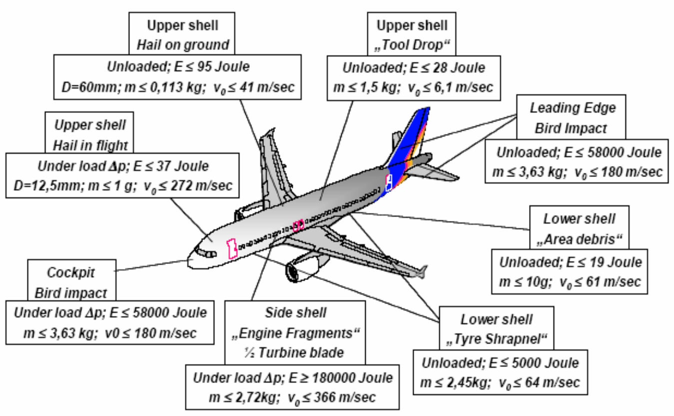

Fig 5: Impact scenarios for a fuselage structure [31]

Composite structures are particularly susceptible to delaminations which reduce their load carrying capacity. Delamination may arise during manufacture or from pre-service or in-service impact damage and may be invisible or may occur in concealed or inaccessible regions. Figure 5 depicts potential impact damage sites for the design of a composite fuselage for a large civil transport aircraft. Under aircraft certification requirements, the ultimate residual strength of the structure must be maintained for damage which may grow from an undetectable (via NDI) size over a defined inspection interval. Civil aircraft manufacturers have traditionally chosen a no-growth approach for non-visual damage [31 - 33] implying that structures with this type of damage will carry design ultimate loads for the operational life of the aircraft. They also impose the requirement that visible damage will not reach a critical size under limit load conditions over two inspection intervals. It must also be demonstrated that the structure can carry continued safe flight loads after impact damage that can reasonably be expected in flight and would be immediately evident to the pilot, e.g. unconstrained engine failure. However, limit load capability must be demonstrated if such damage may not be detected by the pilot, e.g. for bird strike on a control surface.

The result of this approach is that the allowable design strain in composite structures is limited to approximately 1/3 of the limiting value for a pristine material. Figure 6 illustrates the contribution of the various knock-down factors to the design strain. The effect of impact damage accounts for up to 30% of the allowable failure strain. If these uncertainties were eliminated or reduced through SHM, there is a potential for the design allowables to be almost doubled, and similarly for in-flight impact, the ratio between safe flight loads and limit loads could be as high as two.

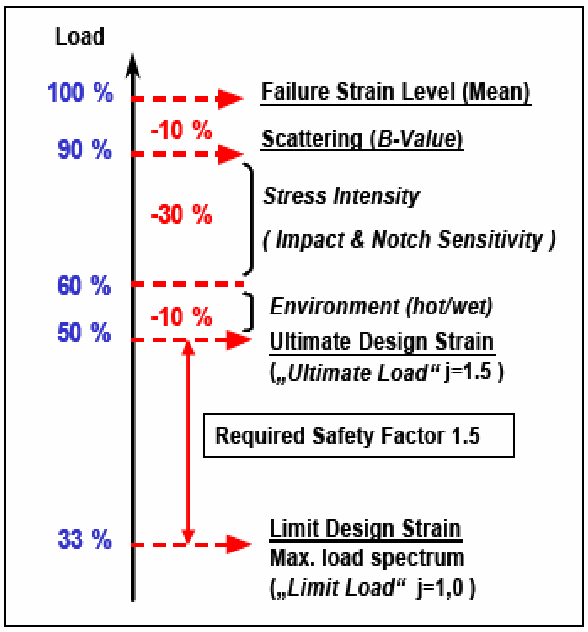

Fig 6: Knock-down factors on design strains [31]

5.2 Consequences of SHM

SHM systems could be implemented for the following cases:

- Detect the presence of defects and damage in the structure at sizes smaller than those currently assumed for design and certification;
- Alert the pilot/operator to in-flight incidents;
- Enable monitoring of the growth of defects and damage; and
- Reduce effective inspection intervals.

Such systems would allow the more widespread adoption of a monitored damage growth philosophy to be used in the design of composite structures, resulting in significant savings in structural mass, of particular importance for structures that are significantly over-designed due to inspection access issues. By detecting the presence or development of critical defects and damages, structures could be designed with higher design allowables. Such systems could also allow higher design loads for in-flight damage because the pilot can be immediately notified and adjust flight behaviour to suit. Perhaps the most importance use of SHM systems would be to change the maintenance philosophy for composite structures from that based on aircraft use to one based on the condition of the structure – maintenance would only be performed when actually required.

However, reductions in section thickness due to more efficient designs may lead to changes in failure modes and the expected efficiencies may not be fully realised. Reduced sections may lead to buckling in the operating load range necessitating postbuckling design for composite structures for the additional efficiencies to be achieved. While commonly applied to metallic structures, postbuckling in composite structures has been limited due to concerns related to both durability and accuracy of design tools. Composites, unlike metals, do not provide stress relief through yielding for the high local stresses experienced during postbuckling. Improvements to design tools to enable accurate prediction of behaviour well beyond buckling are the subject of current research [34]. Buckling can also induce large through-thickness stresses, particularly at the interface between stiffeners and skin of integrally stiffened panels. These stresses may lead to changes in the failure modes, specifically skin-stiffener separation, which is of particular concern to designers and certification authorities. Tools to accurately predict the development of stiffener separation and the criticality of delaminations or stiffener disbonds in postbuckling structures are the subject of current research [35 - 39]. The implementation of SHM to detect such failures may overcome some other current design uncertainties [40].

Higher working strains may also impinge on the durability of composite structures. To date, fatigue has not been considered a major problem because the reduced design allowable strains are below the material fatigue threshold. In the event that SHM systems facilitate the use of higher design allowables, the extent of these improvements may be limited by fatigue considerations. A no-growth approach to composite fatigue substantiation is practical because of low design allowables and correspondingly low operating strain levels together with the characteristic flat S-N curve for composite structures [41]. For typical carbon fibre reinforced composites, significant fatigue damage occurs only at strain levels above approximately 60% of static strength. However, once growth commences, its progression is generally rapid and, consequently, the no-growth option for composites is currently applied [2]. For example the S-N curve for damaged stiffened panels subject to compression fatigue loading (Figure 7) shows that fatigue may not be a problem when the working stress is 33% of failure, but may be a serious problem if the working stress is increased to 53%. On the other hand, SHM may be useful in detecting fatigue damage growth even if it is relatively rapid.

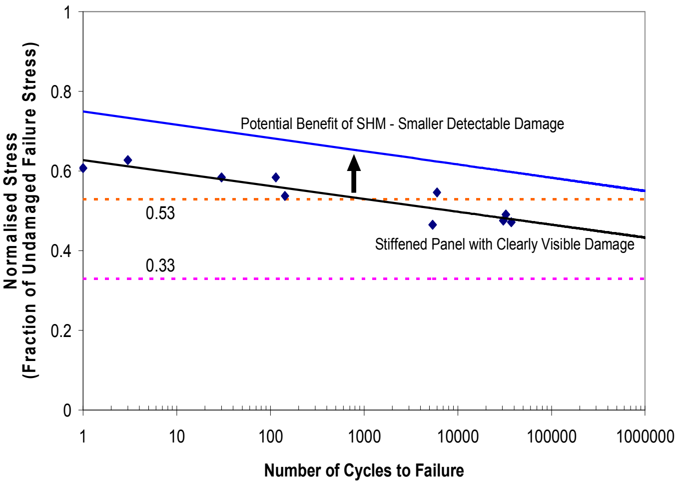

Fig. 7: S-N curve for stiffened panel with stiffener damage, adapted from [42].

6 SHM for Repair

Bonded composite patches are often used as an economical repair strategy to restore the strength of heavily loaded aerospace composite structures after non-catastrophic damage. Significant cost savings may be realised over component replacement. However, due to the uncertainty of longterm adhesive performance and the inability to continuously assess the repair condition, current design practices are inherently highly conservative. In fact, the present requirement for bonded repairs stipulates that the structure in the repair zone must have an acceptable residual strength that is typically 1.2 times the design limit load in the absence of the repair [44]. This places severe restrictions on the application of bonded composite repairs, allowing them only to be used to restore the residual strength of a structure, rather than its operational strength. Where the residual strength is completely lost due to damage, the structure cannot be certifiably repaired, however technically feasible this may be.

The advent of structural heath monitoring technology brings new opportunities for composite bonded repairs. Continual monitoring of a repair will give early warning of insipient failure and so allow corrective maintenance.

SHM is relatively easy to apply in the case of a patch repair because the area to be monitored is limited to the patch bondline. Preliminary studies on external patches and scarf patches have given promising results for both strain-based SHM using optical fibre sensors and for a vibration based techniques [45,46].

7 Conclusions

The use of Structural Health Monitoring is acknowledged as a key to achieving technological leaps in the design and operation of engineering structures. Nowhere is this more relevant than in the use of composite materials for high-value assets such as aircraft, marine vessels and civil infrastructure. The nature of composite materials gives engineers the opportunity to design and manufacture a structure from a micro-level (or even nano-level) up to the macro-level, and in doing so transform it into a smart-structure through the incorporation of developments such as SHM.

However, there are a number of technological challenges that face the principles and practice of SHM before it can realise its potential. This paper has focused upon the specific illustration of aircraft composite structures as a means of highlighting the issues that face SHM. In other composite industries many of the same issues will also apply.

Within the aircraft industry the benefits of SHM relate to the opportunity for reduced maintenance costs through an adoption of Condition Based Maintenance, together with reduced aircraft weight and improved performance through more optimised aircraft design. In order to achieve these goals, research and development is needed in the following areas:

- Development of validated postbuckling design and analysis tools to accurately predict the behaviour of thinner, more efficient structures.
- Material models that accurately predict damage evolution at high strain levels and under increased through-thickness stresses, with the possible need to incorporate composite fatigue analysis.
- Validated diagnostic systems that can identify the size and location of damage within the composite structure to the required accuracy.
- Validated prognosis methodologies to predict the structural integrity of the damaged structure.
- Robust techniques for sensor embedding and connection.
- Power and data handling equipment compatible with aircraft on-board systems.
- Validation of SHM system durability under aircraft service conditions, including repair or replacement procedures for damaged sensors.

Through dialogue with the airworthiness authorities, SHM has the potential to be accepted within the aircraft industry. However, addressing the issues raised in this paper needs to be a focus for future work within the composites and SHM research community if the acceptance of this technology and its potential benefits are ever to be realised.

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