Implementation Strategies for SHM in Civil and Military Applications

Christian Boller
Saarland University, Chair of NDT and Quality Assurance
Fraunhofer IZFP, Campus E 3.1, 66123 Saarbrücken
GERMANY

c.boller@mx.uni-saarland.de

ABSTRACT

Although structural health monitoring (SHM) is a highly attractive technology to implement care has to be taken in a way that this is done in an appropriately. This chapter describes on how to approach this from an aviation point of view and how this can be expanded to other areas such as marine, wind energy generation and civil engineering in general. The results of a case study performed in aviation will underline how important the interaction between design and maintenance is and that the crux lies in the poorer predictability of an ageing structure where the chances of SHM do specifically become apparent. All of the statements made here for civil applications are directly also transferable to military.

1.0 MAINTENANCE AND THE ROLE OF SHM IN AVIATION

Many of the structural components used in aviation are damage tolerant. Damage tolerant structures require a regular inspection at well defined intervals. Since many of the structural components are big and difficult to access as well as to assess from an inspection point of view, maximum allowable cracks can be often of a remarkable big size. No operator of a damage tolerant structure has a mere interest to know much about a damage being below the allowable critical damage because this requires him to take his system (i.e. the aircraft) out of operation for inspection and maintenance without generating any revenue but rather cost. Within the world of aviation related structural integrity, in which fatigue, environmental and accidental damage play a major role, there is a significant margin for SHM to interact. This can be seen from the structure shown in Figure 1, under which the international aircraft maintenance steering group (MSG) works.

That SHM can become a core economic element with high asset structures can be easily shown for a structure such as an aircraft. Every operational hour lost on a commercial aircraft generates a cost of a few thousand Euros per hour each. Therefore, comparing this cost with the hourly rate of an inspector or technician easily allows a number of twenty or more inspectors and technicians to work. Figures are even more extreme when comparing the cost of SHM equipment versus aircraft operability lost. In conclusion, the operability of a high asset value infrastructure is crucial.

In a larger study that analysed aircraft maintenance processes and determined the potential of SHM within aircraft maintenance, a major civil aircraft type flown worldwide was considered [1]. The maintenance process during a D-check, the major inspection an aircraft faces during its operational life, was selected and modelled with discrete event simulation to identify time-critical structural items and estimate the potential benefit SHM could bring. Modelling essentially involved mapping the workflow of steps needed to fully perform the interval and analysing the steps to flag any time-critical items. The generation of information required studying a large number of different types of documents. This started with Maintenance Planning Documents (MPD) issued by the manufacturer. Since times for the different maintenance actions provided by the MPD are rather optimistic, job cards had to be included that better reflected the local specifics of the maintainer and/or aircraft operator.

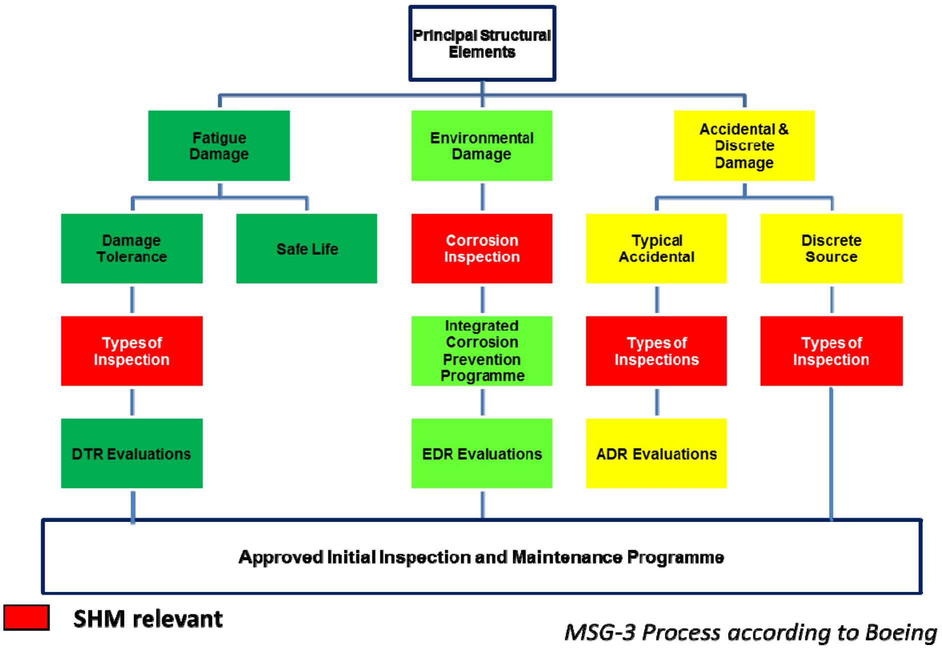


Figure 1: Options for SHM in the aircraft maintenance process.

The maintenance process was modelled using a discrete event simulation tool called Arena [2], which is used to model intervals. Arena has the ability to easily incorporate and analyze stochastic times. An estimate of the individual step times and a probability distribution for modelling is sufficient. The tool works on the basis of a graphical interface with processes to be constructed in a flow chart fashion. However, it is initially important to plan the model before construction. Measuring the aircraft downtime is a key performance criterion in understanding where SHM can be used. The entity moving through the process would therefore be the aircraft. As the aircraft moves along the steps, the duration time will alter. Having the structure of the model such that the aircraft is the entity with maintenance actions as blocks ensures that time-critical items can be traced.

Each item in the D-check was segregated into stages set by planners, and modelled in parallel as process blocks within a stage. The five stages in a D-check can be summarized as:

- Stage 1: Removal
- Stage 2: Inspection
- Stage 3: Defect rectification and rebuild
- Stage 4: Paint
- Stage 5 : Final checks

Figure 2 shows the structure of the D-check, as modelled in an Arena model for greater clarity.

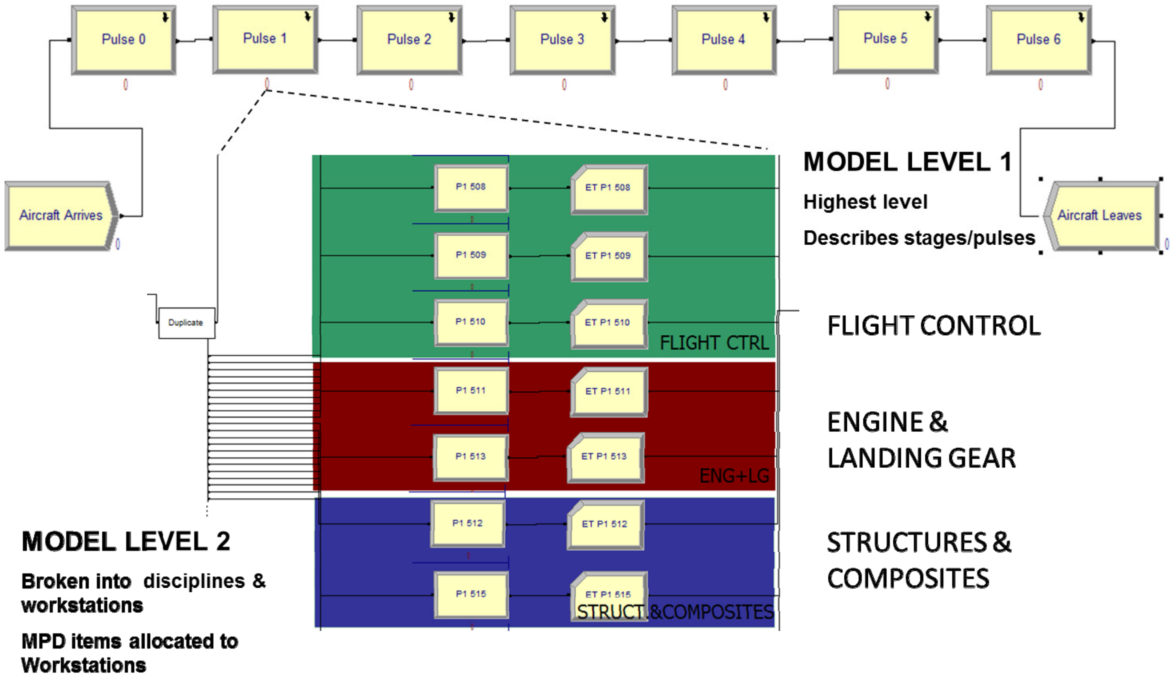


Figure 2: Structure of the D-check model; Notes: Level 1 shows the stages. A section of stage 1 has been expanded to show level 2. Here, items are broken in parallel to the work stations.

With the model established, simulations could be performed in accordance with the procedure described in Figure 3. This procedure can be split into six steps, of which steps 1 to 3 have been already described for the D-check example. For any structural item appearing on the critical path along step 3, an SHM solution has to be determined. This solution is then fed back into the maintenance process (step 4), and its impact is analyzed by comparing the maintenance duration determined with the one achievable without SHM. This may be further varied in case alternative SHM technologies are available (step 6). Further SHM potentials might arise in case the critical path during the maintenance process changes as a consequence of an SHM implementation, and further components with SHM potential might result.

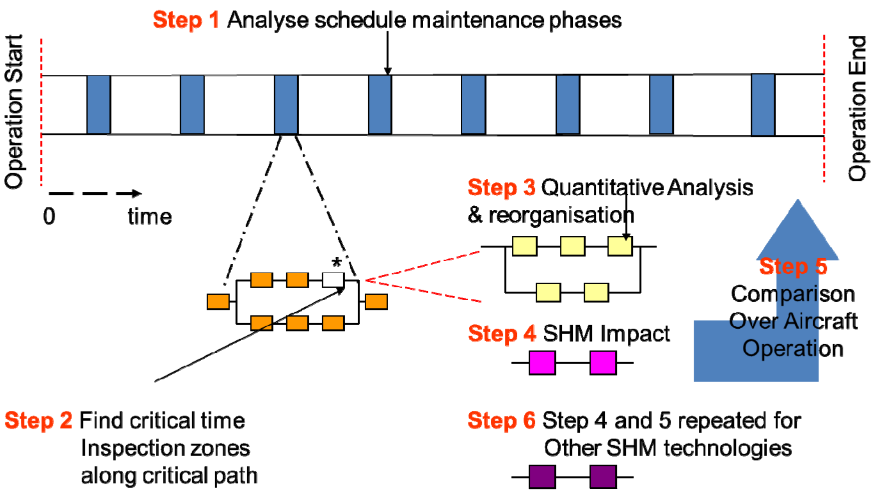


Figure 3: Procedure for analysing the operational life cycle of SHM potentials during the maintenance process of an engineering system.

Maintenance work along the aforementioned D-check was organized in terms of so-called process blocks. These blocks are the result of optimization of the maintenance process. Figure 4 shows the histogram for all process blocks that were considered critical. The number of hits represents the number of times a process block became critical in 100 replications. This is a result of some uncertainties specifically applied to the simulation model. The critical blocks were therefore altered due to uncertainties elicited from the maintenance planners. The process blocks in which SHM could be implemented are highlighted. At those process blocks, a number of SHM solutions were inapplicable (non-inspections, larger visual checks), since the items to be inspected required identical access. Therefore, this access would have been necessary even if an SHM alternative was made available. For this reason, most of the time savings were marginal.

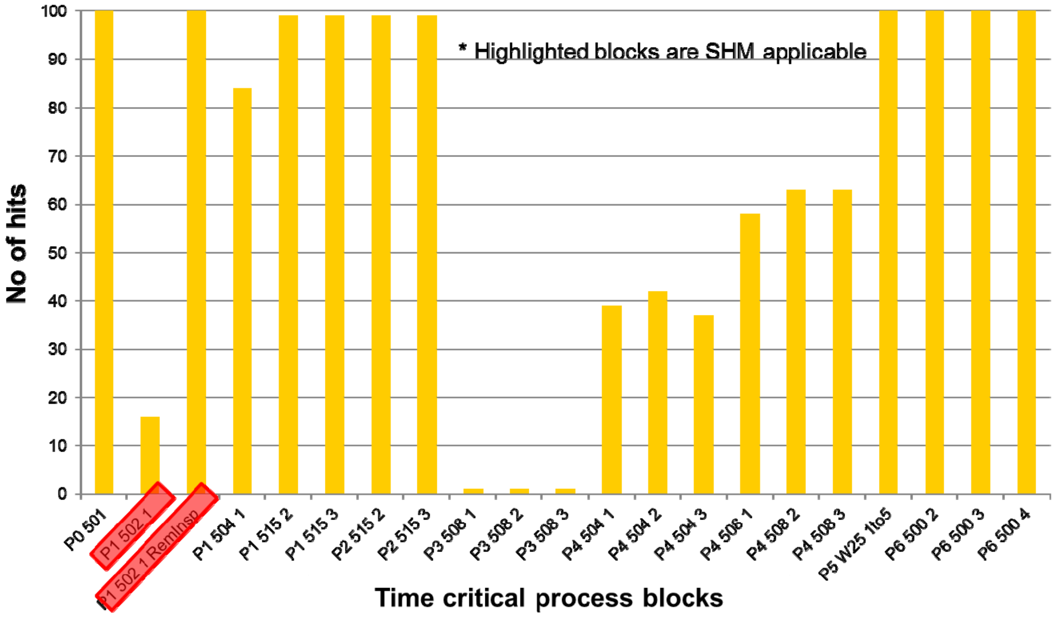
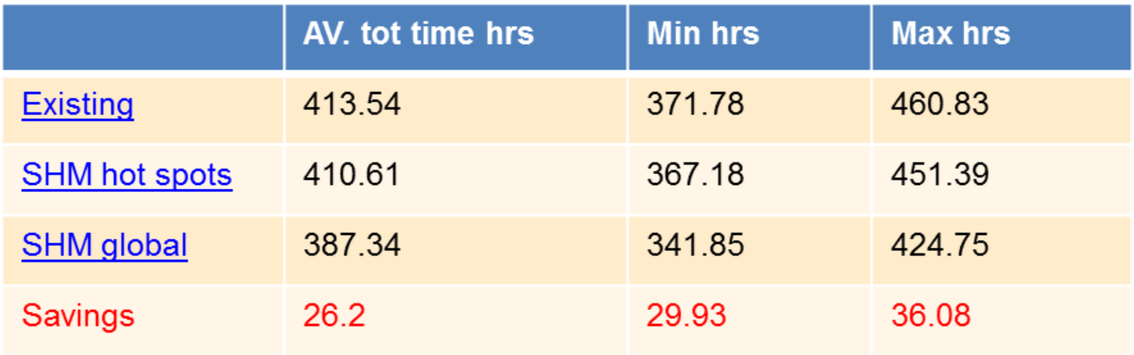


Figure 4: Number of times a process block is critical after 100 replications of D-check simulation considering uncertainties. Highlighted blocks show where SHM is applicable.

Figure 5 shows that the average saving between the existing process and the improved process with SHM at hot spot locations was nearly 3 hours per interval only. The average total saving was less than the minimum saving, as the highlighted critical process blocks were not critical 100 percent of the time when running the replications. Replacement for only a handful of hot spot areas in a D-check would yield only a very small savings. The gain sought in operational capability would not even significantly improve if all the structural components were equipped with SHM; this scenario is called "SHM global" and shown in Figure 5. Even here, the difference might not exceed 36 hours, which is a marginal number when considering the uncertainty and the D-check as a possibly singular event in an aircraft's life. However, those figures provide the perfect match between engineering design and maintenance. In other words, aircraft structures today are designed to be well maintained. Therefore, if maintenance principles change, then they would most likely also have a significant impact on design. Implementing SHM into aircraft designed today or in the past is therefore unlikely to provide the expected benefits.

The following major question emerges as a consequence of the conclusion made above: Does SHM offer any benefit for current aircraft? The answer to that question is 'yes' and the potentials have to be seen in what is called a "drop-out." A drop-out is a damaging situation that occurs unexpectedly over an aircraft's operational life. An example is repairs, which are often not predictable and require specific care over the aircraft's remaining life. Other drop-outs are damages that occur while an aircraft is aging and which cannot be predicted in advance. Drop-outs are most likely to define their own inspection intervals, which most likely will not match the aforementioned optimized maintenance plans.



	AV. tot time hrs	Min hrs	Max hrs
Existing	413.54	371.78	460.83
SHM hot spots	410.61	367.18	451.39
SHM global	387.34	341.85	424.75
Savings	26.2	29.93	36.08

Figure 5: Comparison of the two simulation durations: one modelling the existing process and the other replicating if identified hot spot regions were eliminated.

Consequently, inspections will have to be performed regarding only those drop-outs, which may result in a relatively expensive inspection action. An example where such an SHM impact could be validated is the gantries on the Airbus A300. As shown in Figure 6, gantries are the major longitudinal beams over the wing box of an aircraft. They are exposed to major bending loads of the aircraft fuselage as well as cabin pressure loads, which are downloaded from bolted diaphragm panels into the flanges of the gantries. The complexity of stress states in that region may result in cracks emerging, which need to be detected through inspection and be removed at intervals that are most likely not in line with the conventional maintenance process. Having those locations inspected also requires a substantial amount of dis- and reassembly of various components in the near-field.

In the case of gantries' inspection, the process was initially simulated with Arena by varying the numbers of inspectors and workers involved in the inspection process. The results obtained are shown in Figure 7. It can be seen that by increasing the number of workers and inspectors, the duration for inspecting the gantries will decrease, however not below a threshold value of approximately 120 hours of maintenance. This result has been compared to a solution where an SHM system has been implemented around the locations prone to cracking. This solution would only require a plug to be contacted for inspection in the aircraft's floor and would avoid any disassembly of seats, carpets, floors, etc. Inspection time would also be reduced to 20 hours for an aircraft's remaining life cycle, resulting in approximately 100 hours per aircraft of operability gained or a significant six-digit Euro volume of operational cost.

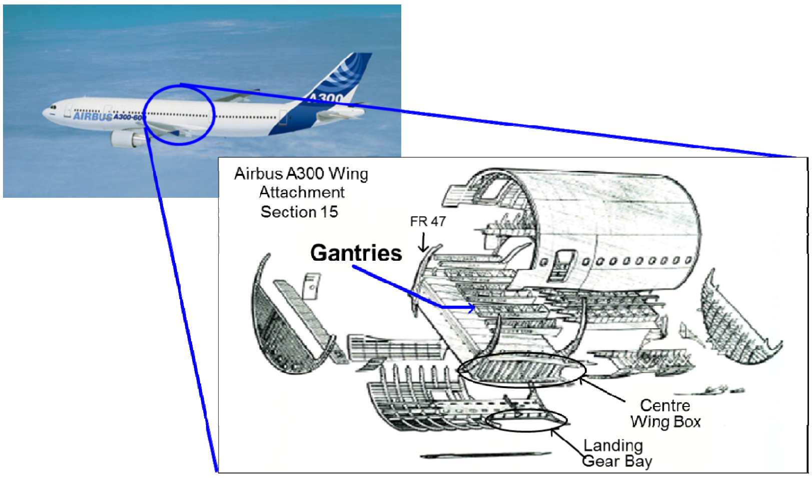


Figure 6: Drop-out item gantries and their location within the aircraft.

Model	Number of MRB Workers	Number of Inspectors	Total Number of Workers	Total Maintenance Time for whole life-cycle (hrs)
1	3	2	5	264.47
2	6	4	10	171.33
3	9	6	15	145.90
4	12	8	20	128.99
5	15	10	25	121.75

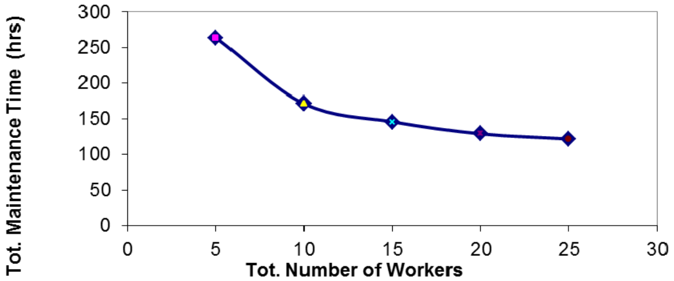


Figure 7: Total life cycle maintenance time for gantries inspection depending on labour involved.

SHM has its short-term benefits, specifically in automating unscheduled inspection processes. This requires flexible solutions being application tailored. Implementing SHM at a product's life cycle onset requires modifying the product's design principles such that an overall economic benefit can be seen. This approach is definitely only possible with products that are designed from scratch, but hardly with those existing today.

With all this done and described so far the question remains why so little SHM is done today in aviation. Some of the reasons for this may be the following:

- Technologies have not demonstrated sufficiently readiness level and reliability
- SHM potentials are not sufficiently quantified
- Aircraft manufacturers only consider SHM for new aircraft which then becomes a design issue and hence a much longer term affair
- Aircraft operators are:
    - not aware of the SHM potentials,
    - reluctant to release their operational conditions (operational issue)
    - afraid of getting more sensors into aircraft (reliability issue)
- Airworthiness authorities are not very well integrated into the technology development and integration process
- The data integration issue is not sufficiently solved, a point that has been associated with the expression of »vertical integration«;
- Insufficient appreciation of activities in neighbouring fields (i.e. engine health management, avionics built in test equipment, helicopters health and usage management).

Looking at all those aspects and somehow problems addressed they do not seem impossible to be solved. However it is the awareness that has to be made, that only can be achieved through an analysis that possibly goes beyond the conventional engineering and natural science issues usually addressed.

2.0 SHM IN MILITARY VEHICLES

Military applications have triggered a lot with regard to SHM because of the harsh environment military vehicles operate in. Another motivation for considering SHM is however also the high asset value many structures have in general. Those do include aircraft as well as marine structures when considering the defence sector specifically. This does however also include civil infrastructure, although this may be less possessed by armies, air forces or navies respectively. A major drive for SHM has also come out of military aviation due to enhanced performance as well as operational life extension. Some interesting applications of SHM have been developed for marine applications too. Aviation and marine are therefore the examples referenced in the sub-chapters below.

2.1 Aviation

SHM in military aviation has a fairly long tradition. A source where much of this information has been compiled is the Encyclopedia of Structural Health Monitoring published in 2009 [3]. Following the dramatic accidents of the de Havilland Comet aircraft in the early 1950ies the UK Royal Air Force came up with a loads monitoring system that was based on accelerometers measuring load exceedances, from which a fatigue life consumption has been calculated [4]. These activities have been continuously pursued specifically in Europe and have resulted in the operational loads monitoring systems initially tested in the Panavia Tornado fighter aircraft and now realised in the Eurofighter Typhoon aircraft where operational loads are monitored and 16 load critical locations (Figure 8).

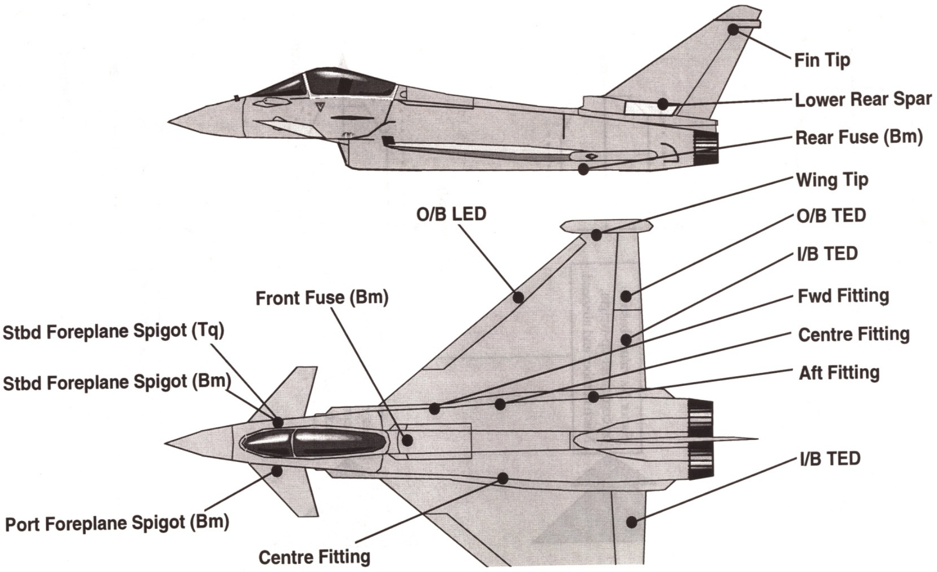


Figure 8: Operational loads monitoring locations on Eurofighter Typhoon aircraft.

In 1992 AGARD organized for the first time a conference devoted to »Smart Structures for Aircraft and Spacecraft« [5] along which the idea of implementing SHM into military aviation became apparent. Optical fibres and piezoelectric transducers were addressed for monitoring a variety of aspects such as structural loads or damage in composite materials which were major issues due to emerge in military aviation at the time. SHM for military aircraft also with regard to fatigue related structural assessment was possibly first described here in [6], addressing the breadth of materials ranging from metals to composites and even considering the operational environment as well as the link to conventional fatigue life evaluation. The idea of implementing fibre optical sensors into military fighter structures arose from British Aerospace at that time as well [7] and Mc Bride et al. in Canada had been performing acoustic emission tests during flight [8]. In 1996 AGARD (now STO) issued for the first time a lecture series on »Smart Structures and Materials: Implications for Military Aircraft of New Generation« [9]. Along those lectures a first assessment trial was made with regard to possible gains in structural weight when implementing SHM even into a composite materials structure [10]. Activities involving SHM concepts and activities on F 18 fighter aircraft in the USA have been well reported in [11] where work was mainly related to concepts of using acoustic emission technology.

Buderath [12] gives an overview on fatigue monitoring in fixed-wing military aircraft where he describes the standards and the tracking in fatigue monitoring used today, which mainly consists of evaluation, testing and inspection to identify the fatigue critical areas. Those areas have to be inspected at defined intervals and hence monitored, a process that has to be run even over an aircraft's operational life and which may even decide upon operational life extension. A keyword addressed in that context is condition based maintenance (CBM) where the inclusion of SHM could turn out to be beneficial. A large issue already today is the handling of operational loads data generated which becomes an additional issue when those will be added by data recorded for damage monitoring. A major discussion in that regard is the need for on-board and off-board data processing. With fighter aircraft on-board processing may become more relevant in the context of battle damage where measures do have to be taken with regard to structural damage even during flight. Within the frame of operational loads monitoring strain-gauge based monitoring is still a method of primary choice where this way of monitoring may even be used in so call damage critical (hot spot) areas to monitor a critical damage such as a critical crack length or crack opening displacement. Maintenance scheduling and structural damage tracking in military aircraft is a process being very much based on statistical sampling. Three different categories are differentiated which includes individual aircraft tracking (IAT), temporary aircraft tracking (TAT) and selected aircraft tracking (SAT) respectively. Data recorded is then fed into a mathematical model which through data evaluation is able to configure the appropriate maintenance plan. This approach has not only been limited to Europe but has also been applied to F-18 users such as in Australia [13].

The operational loads monitoring system implemented today in the Eurofighter Typhoon aircraft is able to generate load spectra that can be used for follow-on fatigue life evaluations. This information being part of the SHM system is then fed together with similar information from the engine monitoring unit (EMU) into the integrated processing unit (IPU) which is a part of the various bus systems of the aircraft itself serving flight control as well as avionics [12]. This approach and system can be upgraded in a sense that data generated from damage monitoring might be able to be fed in as well. Also for the military transporter A 400M a monitoring and diagnostic system (MDS) has been developed which allows SHM data to be accommodated accordingly.

Implementation of a Smart Layer piezoelectric patch manufactured by Acellent Technologies [14] has been placed around the patched repair of the keel beam of a Lockheed F-16 fighter airplane [15]. Objective of the work was mainly to determine the physical implementation process as well as the way the SHM system performs even under true operational (i.e. flight) conditions. As mentioned with the Airbus A 400 M before military transporters today are increasingly equipped with operational loads monitoring (OLM) systems. In [16] the implementation of OLM systems to aircraft such as C130 transporter or the KC30 tanker of the UK and Australian Royal Air Force has been specifically described. OLM systems need to be well calibrated. During flight they generate a significant amount of data with 1 GB of data generated in engineering terms during a 4 hrs. flight, easily leading to TBs of data when a longer flight history is considered. The complexity of strain gauges implemented on these aircraft has led to the idea of using artificial neural networks to identify specific load patterns on the KC30 tanker. Validation of operational loads spectra has also been performed on a Dominie TMk1 aircraft which is a business jet that has been used for military operations and for specifically validating OLM with respect to different load spectra as well as crack propagation life [16].

As regards defence, unmanned aerial vehicles (UAV) are another important field where SHM can be of major interest [17]. Besides the fact that the vehicle is unmanned, motivation for using SHM is to meet requirements set with regard to improved decision support for autonomous mission execution, reduction of mission, operation, and support cost, and contribution to the certification process of the UAVs. Figure 9 summarizes the design requirements and the process with more details for a concept outline to be found in [17].

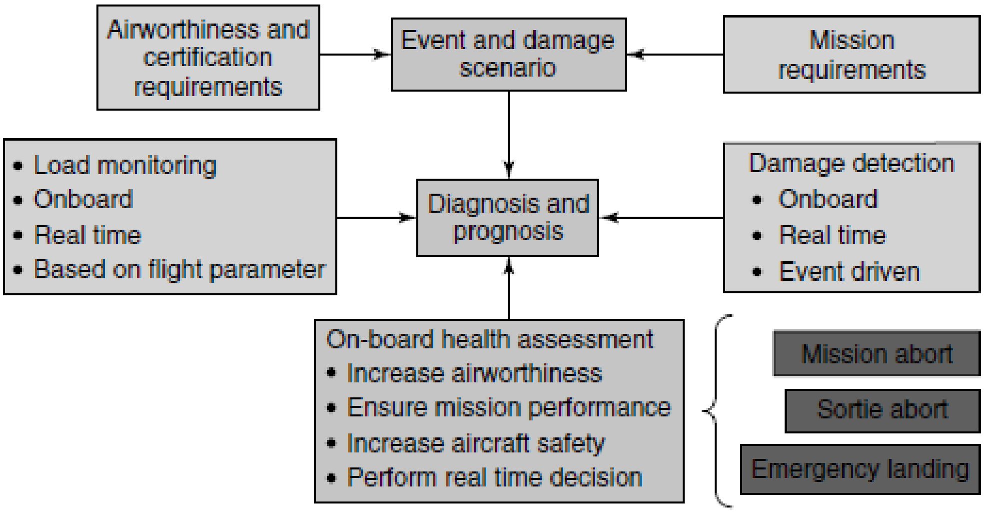


Figure 9: Design requirements and process for SHM implementation in UAVs [17].

Helicopters are a subject of monitoring too. The key system with regard to SHM in helicopters is the health and usage monitoring system HUMS which was gradually introduced into those vehicles after different failures during offshore flights occurred as a result of cracking in gear rods and a relatively short crack propagation time. Since load spectra specifically of connecting rods in helicopters are mainly of a constant amplitude nature and cracks emerging do result in vibrations, HUMS has been mainly configured as a vibrations monitoring system including a variety of signal processing features. A description of HUMS can be found in [18,19]. According to [19] HUMS can detect nearly 70% of the mechanical defects generating in helicopter rotational parts keeping in mind that around 40% of the helicopter accidents are fatigue/component related. Next generation HUMS is said to become more integrated and to look into technologies for fault and damage including even crack detection as well as to actual operation and usage generally. Damage tolerance, probabilistics and prognostics will become essential elements of HUMS therefore as well.

Corrosion is another significant obstacle deteriorating structures in general. Although it is difficult to monitor there is a different activity ongoing in combining a variety of sensor options being available and combining those with diagnostic and prognostic models. This has been done from an aviation point of view in a larger study performed by DSTO in Australia and has been well described from an SHM point of view in [20].

2.2 Marine

Another area related to military vehicles where SHM can become of significant interest with respect to structural size as well as to asset value is marine structures and here specifically ships where a detailed description of the state of the art is provided in [21]. Current SHM activities in this field are related to loads monitoring by using strain gauges as well as accelerometers to determine and describe the load spectrum which can be rather complex and not easy to be understood. Once available the load spectrum is then used for fatigue life evaluation where global and local strains have to be correlated from a structural mechanics point of view. Principally damage could also be detected keeping the size of the structures and the allowable damages in mind. However this way of monitoring is still a desire and requires further development.

3.0 SHM IN WIND ENERGY GENERATION

Wind energy generation is a business booming those days. This boom is not just due to the trend towards renewable energies but also with regard to enhancing the output of each wind energy power plant. As a consequence wind energy power plants get continuously bigger in size which can be seen from the chart provided in Figure 10 below. When just looking at the span of the rotor blades those blades do exceed the span of today's biggest passenger aircraft the Airbus A380. In view of those rotor blades continuously rotating and operating over the ground in an environment being possibly the most detrimental to an aircraft with regard to humidity and turbulence, a structural designer might appreciate the loading conditions such a rotor blade is going through. The pace in wind energy rotor blade development may therefore request the need for monitoring in various regards.

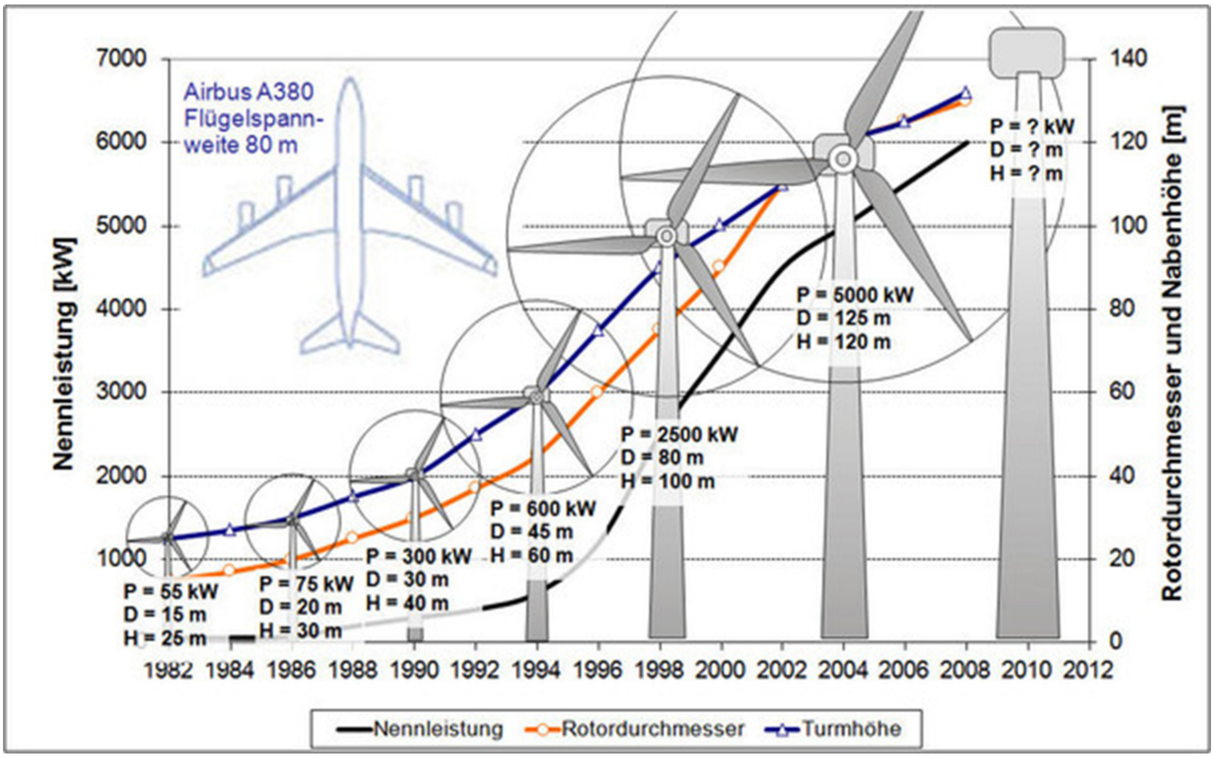


Figure 10: Wind energy power plant development over the past 20 years (Source: www.ski-consult.de).

From the various components of a wind energy power plant the rotor blade is possibly the component being most exposed to damage. In many of the regions rotor blades operate those are exposed to humidity which can lead to icing, The longer a rotor blade is in size the more severe icing becomes where the mass of the ice can achieve 3% of the weight of the rotor blade easily. This weight leads to an increase in imbalance and dynamic loads in general. Furthermore ice may fall off and hit the rotor blade following which may be a source of impact damage to the rotor blade. Another effect due to hit the rotor blade is lightning strikes. More than half of the lightning strikes hit rotor blades directly where around a third of the damages caused hit the rotor blade itself. It is also interesting to see how the risk of repair of the different components of a wind energy power plant increases with operational age (Figure 11). While the risk of repair starts with sensors and controls it gradually moves up to the larger and also more costly components. It is however remarkable to see that gears may already be affected quite early during the life cycle being a sign that loads applied to those gears may not be very sufficiently understood or may alter significantly, being an indication that loads monitoring could be of some significant help.

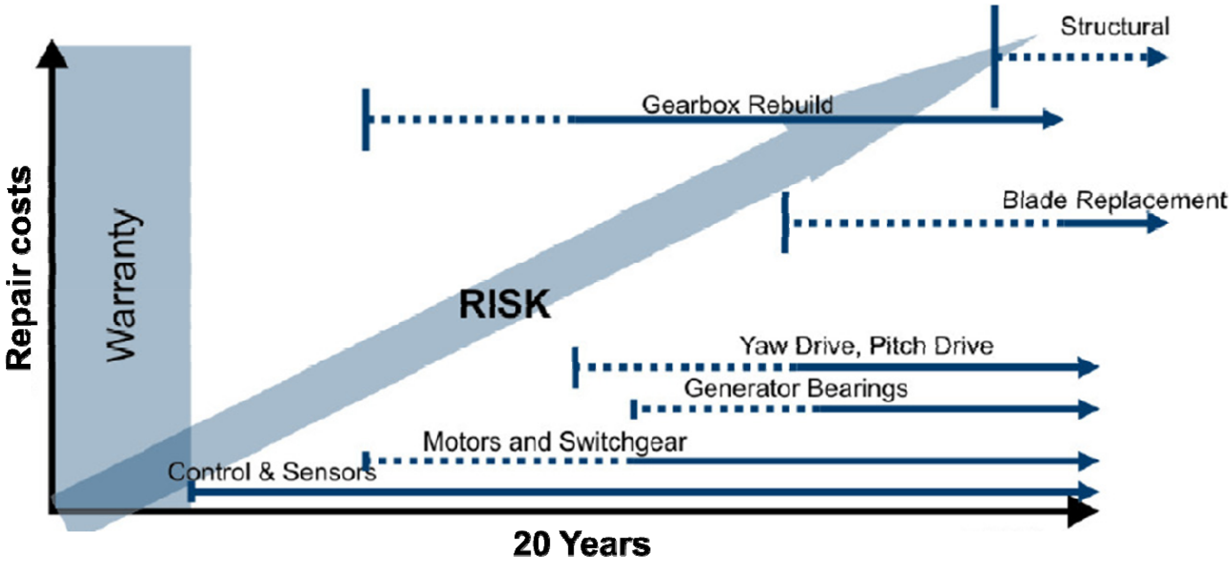


Figure 11: Risk of repair cost over the life cycle of wind energy power plants (Source: US Dept. of Energy).

As regards failure of the rotor blade one out of five rotor blades do fail per year in average which leads to a downtime of around six days in average and a revenue lost respectively. Condition based maintenance is therefore a rewarding measure to be taken which can lead to savings of 10% and possibly even more in life cycles cost.

There are different measures that can be taken to monitor the condition of wind energy rotor blades. To avoid complexity and risk of an SHM failure a general rule with respect to SHM implementation is to keep the number of sensors to be implemented low. This is achieved when considering the implementation of loads and modal analysis sensors first. Sensors and sensor systems in that regard having been successfully used is conventional vibration sensors such as being based on piezoelectric transducers, optical fibres, MEMS and possibly others. A system developed and implemented in that regard has been developed by Wölfel Beratende Ingenieure with major inputs from Fritzen et al. [22]. The system developed and shown in Figure 12 consists of a sensor unit implemented in the rotor blade which monitors acceleration, pitch and yaw of the blade over time. This information is fed into a data acquisition unit placed in the rotor hub that transfers the data to a data processing unit (DPU) in the nacelle. This DPU allows for processing of the data recorded and performs a trend analysis with regard to the observations made. The trends can be related to icing as well as any other imbalance occurring in a rotor blade as a result of damage allowing the wind energy power plant to be shut down before critical damage (i.e. collapse) may occur.

Since allowable damages in wind energy power plants such as delaminations can easily range into the tens of centimetre range they may be well detectable with the modal analysis approaches described so far. Modes may however also be detected through a series of optical fibre Bragg grating sensors placed along the rotor blade.

An alternative to modal analysis for damage detection are acoustics based methods such as either acoustic emission when considering a passive mode only or acousto-ultrasonic based guided waves when considering an active mode. In both cases the potential area where damage is due to occur has to be known or a network of transducers has to be established such that the location of damage can be identified once damage occurs. The transducers to be used in that case are piezoelectric patches which need to be attached on the structure's surface as shown in Figure 13. Locations on where to place those patches best may be obtained from a numeric simulation as shown on Figure 14 below. Along different full scale ground tests this principle has been validated and it could be shown that undulations resulting from manufacturing as well as delaminations could be well identified when keeping the size of allowable damages in mind. Figure 15 shows the superposition of results obtained from acoustic emission and acousto-ultrasonics respectively providing an impression of state-of-the-art achievements with wind energy rotor blades so far.

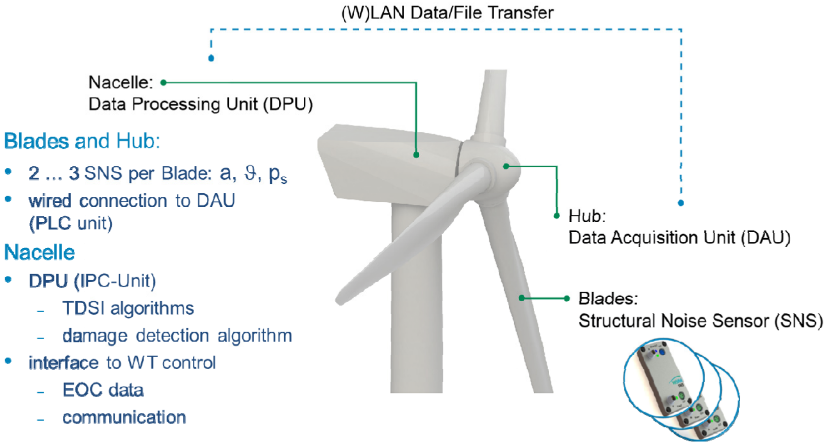


Figure 12: Operational Modal Analysis System (Source: Wölfel Beratende Ingenieure).

Figure 13: Piezoelectric patch attached to an inner web spar of a wind energy rotor blade.

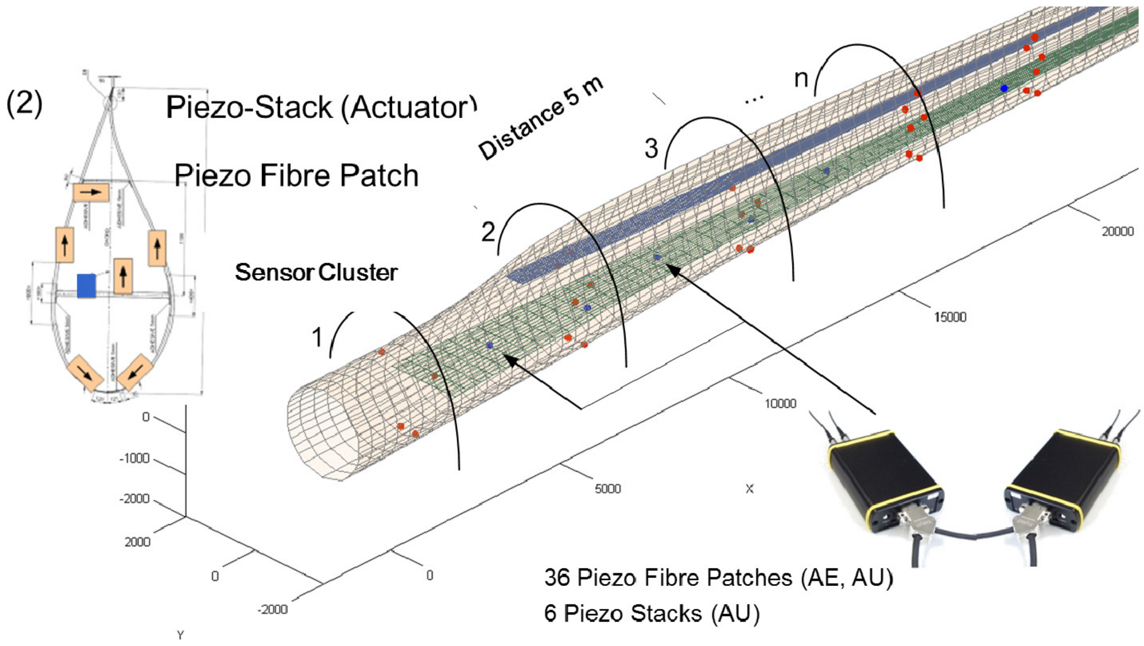


Figure 14: Numeric modelling for transducer placement identification.

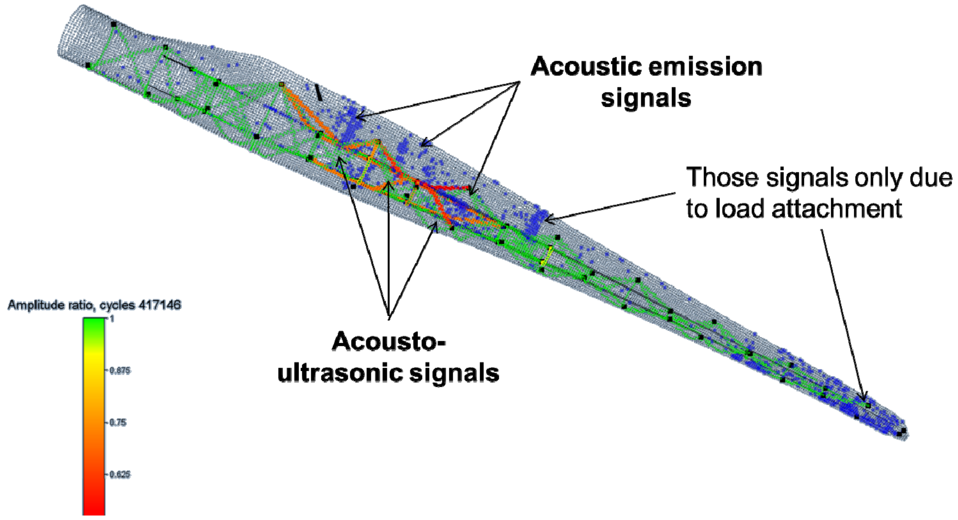


Figure 15: Superposition of results obtained from monitoring a damaged wind energy rotor blade by acoustic emission and guided waves acousto-ultrasonics.

4.0 MONITORING OF CIVIL INFRASTRUCTURE

An increasing amount of civil infrastructure (i.e. buildings, roads, bridges etc.) has become an issue with regard to ageing. Life cycle management therefore becomes an issue. According the Federal Highway Administration nearly 70% of bridges and roads in the USA need to be inspected regularly [23] with inspections being purely visual and inspectors present on site. Apart from bridges any other type of infrastructure is currently not subject of clear regular inspection although this may become increasingly relevant with an infrastructure's advanced age. With many of the infrastructural buildings to be inspected inspections can become dangerous for the inspector as well as time consuming. Those inspections will again be mainly visual. Automation of the process using a robot (or multiple robots) equipped with digital cameras in the first place may be an option interesting to be explored.

4.1 Micro Aerial Vehicles for Building Inspection

The inspection method used is based on a micro aerial vehicle (MAV) equipped with a digital camera underneath as shown in Figure 16. The MAV is flown remotely and scans the building to be monitored. The camera is set to be continuously triggered with a frequency of 3Hz, which is also known as the time based method of image capturing. Even though the robot is fitted with a GPS receiver and has GPS guided capability, the entire flight process is manually controlled. This is due to the lack of signal when the vehicle flies close to a wall. The autopilot only provides auto-stabilization and altitude hold.

Figure 16: Octocopter MAV system with digital camera.

To successfully run the photographic monitoring initially, a flight route well planned is most essential for which the two recommended solutions are shown in Figure 17 with the horizontal scanning route to be preferred when the camera image ratio is 4:3.

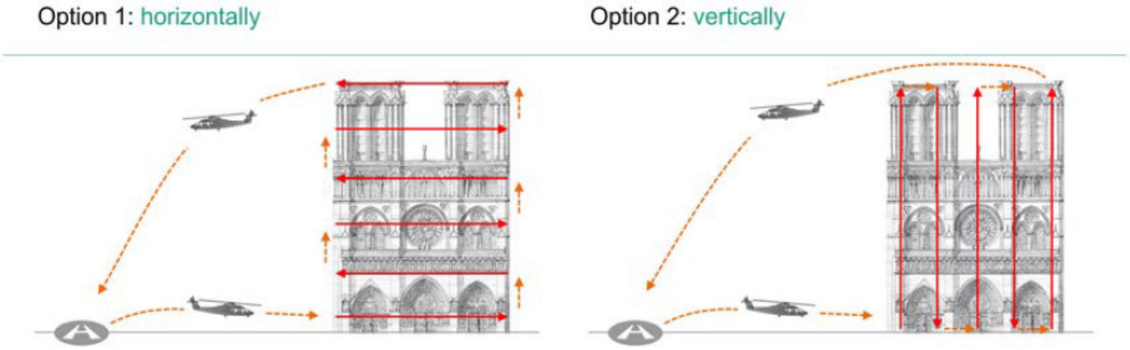


Figure 17: Efficient flight route planning for building inspection.

To monitor a building a volume of several GB of data is recorded which is equivalent to thousands photos. After having all the pictures taken, the major challenge exists in stitching all the images together. This challenge increases with the decrease of the damage size to be reliably monitored and hence the resolution of the photographs obtained. Further details regarding the image retrieval process can be found in [24].

A building consisting of 7 floors (around 30 meters high and around 100 meters wide) has been recently inspected. The challenge of monitoring this building has been in the huge similarities consisting of more than 400 windows of the same type. Thousands of images were taken during the recording process and stitched together on a semi-automatic basis with manual corrections still to be made in the end. The complete stitched image of the building can be seen on Figure 18. The reason why portions of the image turn out to be lighter than the other ones stems from the fact that two missions were flown on different days with different sunshine conditions. The image shown in Figure 18 has been further extended to a 3D image where each location of the building can be zoomed in obtaining images of the one shown in Figure 19 and even better.

Figure 18: Fully stitched image of the building to be monitored.

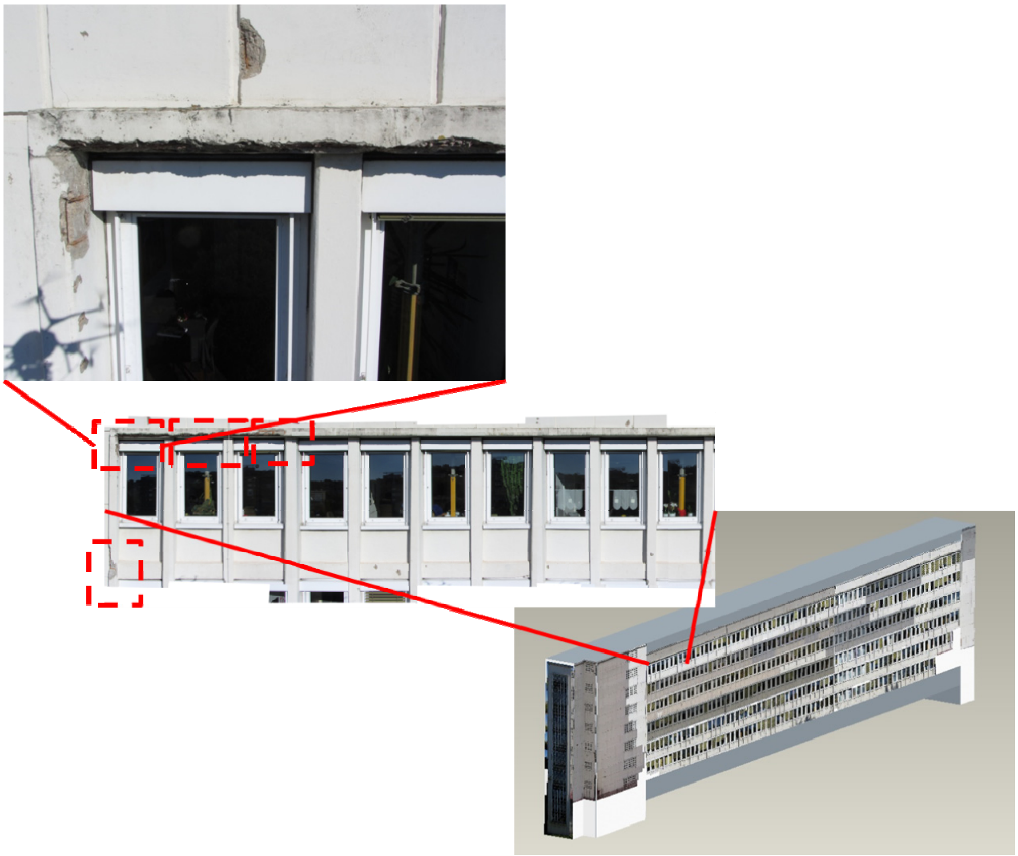


Figure 19: Single image (top), manually stitched image (middle) and stitched sections added onto CAD model (bottom).

The images obtained do allow for crack patterns to be recognized even on an automated basis in the longer term. Figure 20 shows an example where a cracking pattern has been extracted from the stitched image allowing further conclusions to be drawn with regard to the damage condition of the structure considered in general.

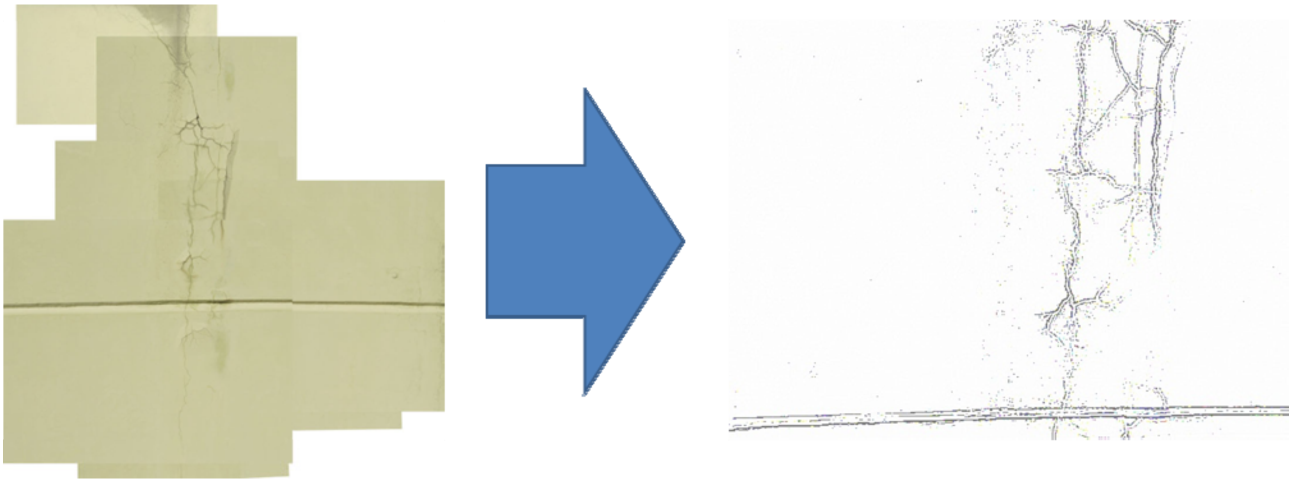


Figure 20: Crack pattern in reinforced concrete derived from photographic image processing.

4.2 NDT Techniques Beyond Visual Inspection

Structural damage seen on the surface may request to understand the sources of this damage that may result from underneath the surface. Considering reinforced concrete as the material to be inspected this requires more sophisticated techniques to be applied. A selection of options being successfully applied are shown in Figure 21.

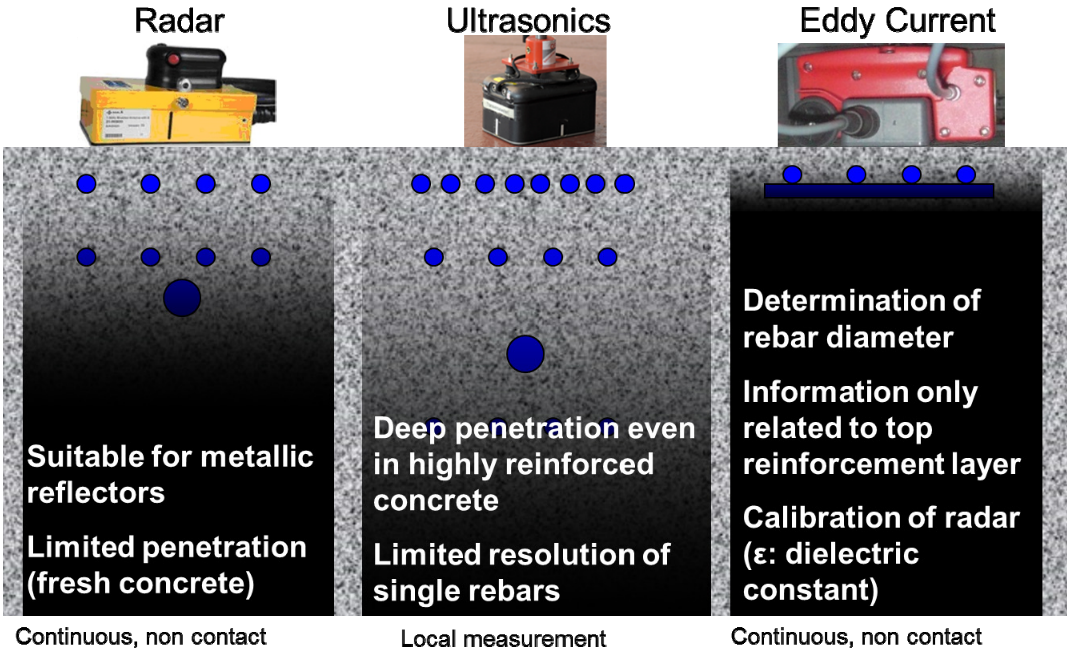


Figure 21: Crack pattern in reinforced concrete derived from photographic image processing.

Radar has the advantage of recognizing metallic reflectors such as rebars and tendons, although their penetration into the material is limited. However concrete coverage is a major issue and source of damage in reinforced concrete structures where radar can be very beneficial. In contrast to radar ultrasound has the advantage of much deeper penetration however with the disadvantage of lower resolution specifically what regards the detection of the rebars. This can however be further complemented when including eddy current which again mainly monitors effects closely under the surface but allows for a more precise measurement of the rebars and hence a calibration of the other NDT methods being used. What becomes apparent here is, that the combination of data obtained from measurements with different NDT techniques can even allow a view into a material as 'exotic' as reinforced concrete. This has been applied to a variety of different scanners where the example of the BetoScan scanner [25] is shown in Figure 22 below.

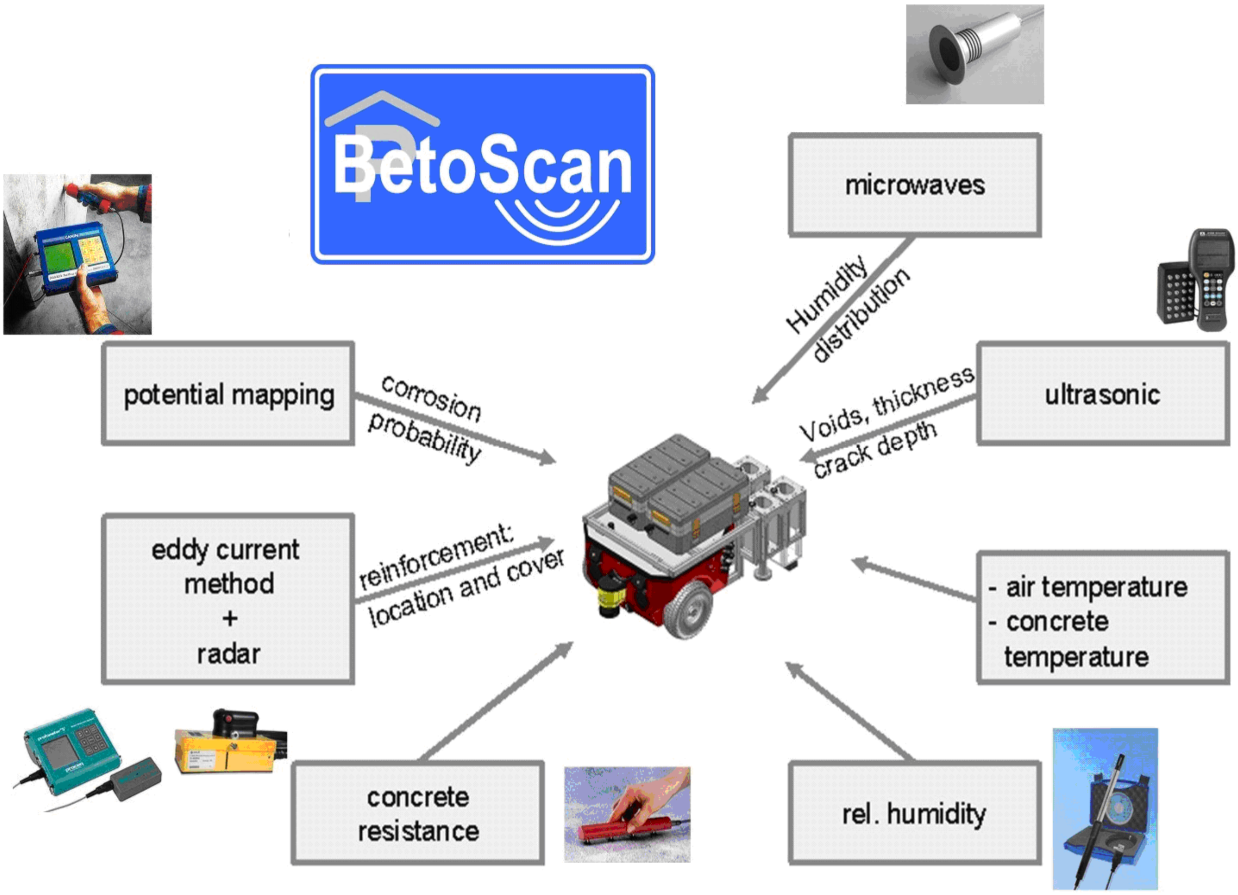


Figure 22: Modular NDT robot BetoScan for automated inspection of parking decks.

Another interesting field of inspection is stay cables specifically used on bridges which may fracture from corrosion and therefore require inspection. As long as the stay cable is freely accessible it may be inspected with a crawler that usually operates on a magnetic basis where an example is provided in Figure 23 (left). Often however the stay cable is grouted into concrete material where it may deteriorate as well and not be easily accessible for inspection. However even in those cases some option for inspection exists in a way that an electromechanically ultrasonic guided wave as shown on Figure 23 (right) can be generated and will be sent into the grouted area, allowing damage such as mainly corrosion to be observed to a certain extent.

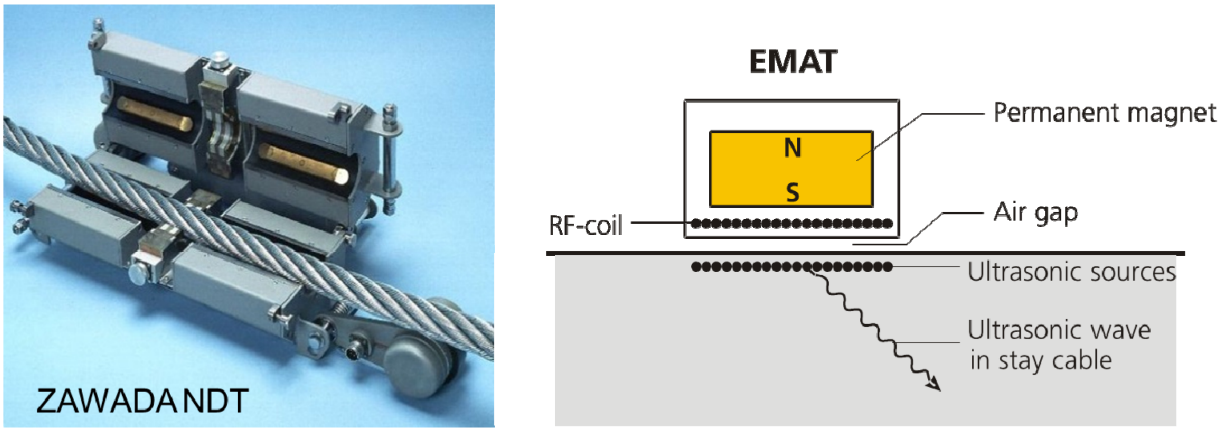
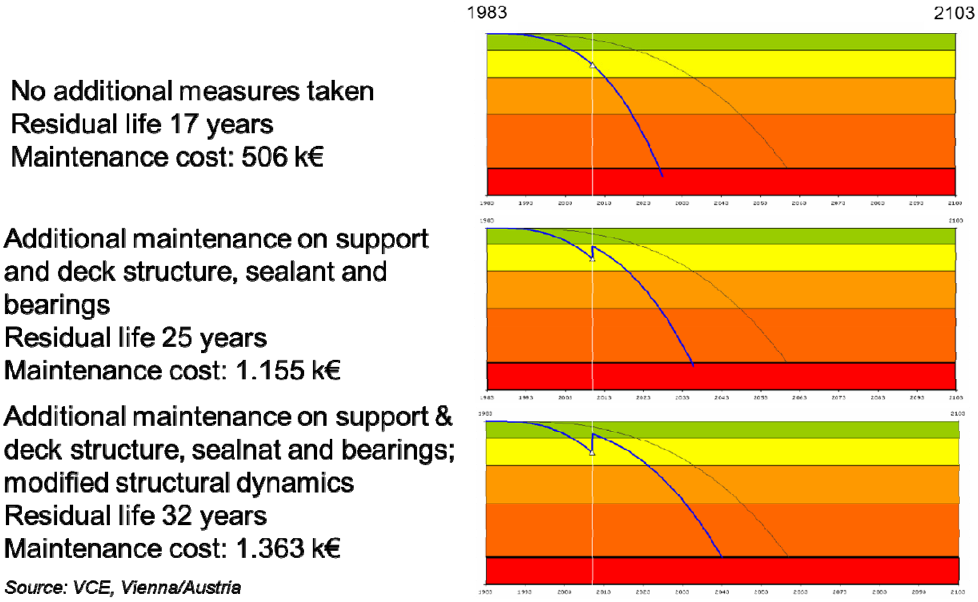


Figure 23: Monitoring of stay cables: crawler for accessible regions (left), electromechanically activated ultrasonic guided waves for grouted zones (right).

4.3 Infrastructure Assessment

With the increasing number of infrastructure ageing there is an increasing need to get this infrastructure assessed and its life cycle managed to a much larger extent than this has been done before. Along the EU funded project »Industrial Safety and Life Cycle Engineering« (IRIS) [26] some interesting assessment tools have been developed which allow the safety of a structure (a bridge in the case analyzed) to be modelled over the life cycle [27]. This leads to the degradation curves as shown in Figure 24 where three maintenance options have been considered for a bridge built in 1983 and due to last for another 17 years minimum at the time of assessment which was in 2010.



Source: VCE, Vienna/Austria

Figure 24: Risk assessment analysis for residual life of the highway 202 bridge in Wayne/NJ, USA.

The charts shown in Figure 24 demonstrate risk levels on a traffic light scale. Degradation and risk do progress on a nonlinear basis as to be seen from the different charts, where a scatter band is indicated for the worst and best case respectively. Those curves look similar to the crack propagation curves used in damage tolerance considerations being just symmetric to those along the horizontal axis. With this in mind it becomes obvious that damage tolerance design now even becomes a design and management issue for civil infrastructure and a tool for structural management in general. The parameter for the vertical axis of the charts shown in Figure 24 is safety or risk which can be associated with cost as well. Hence cost figures could be derived from those diagrams, becoming an interesting tool to perform asset management. Those considerations will also allow the value of SHM options to be assessed. Hence a tool is provided in that regard that allows the value of SHM in civil infrastructure to be assessed, at least in principle.

5.0 CONCLUSION

From what has been said it becomes apparent that SHM can have a true value. This value can vary upon the degree of effort that has been placed into SHM implementation. As can be seen from Figure 25, SHM can be implemented as a maintenance measure at any time along the life cycle of a structure and is able to generate revenue to a partially remarkable extent. SHM may however also be included already in the conceptual phase and hence designed into structures such that they would become inspectable right away.

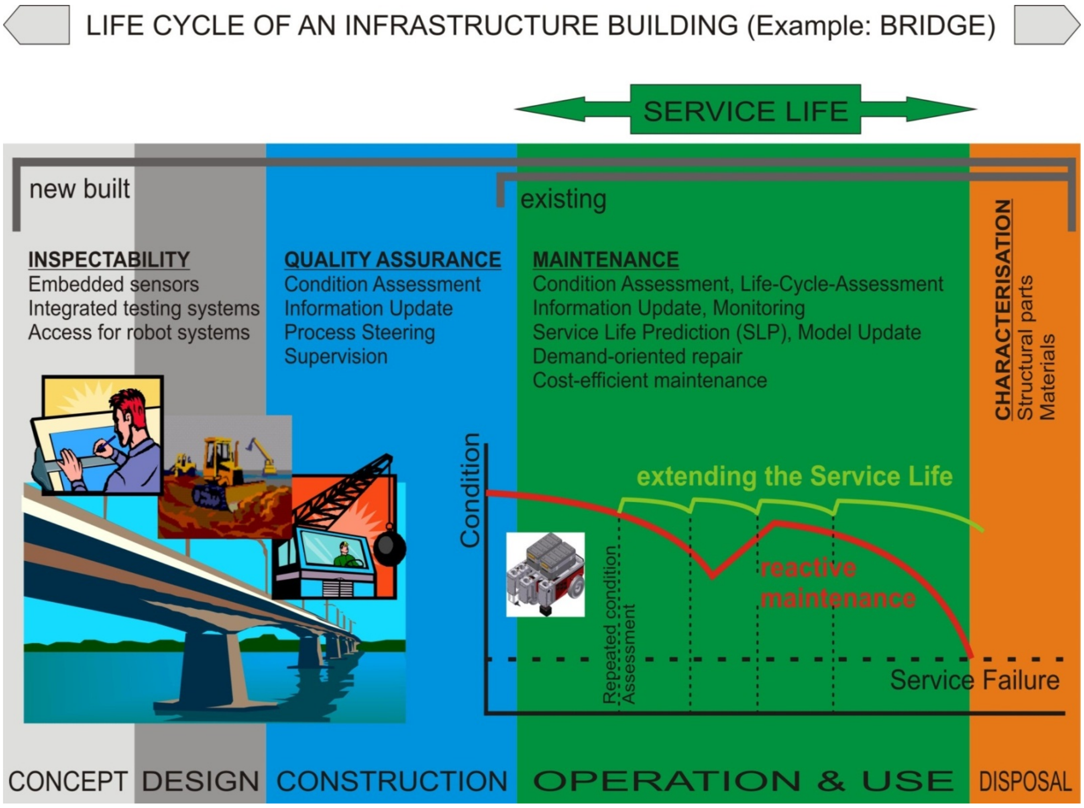


Figure 25: SHM implementation and impacts along the life cycle of civil infrastructure.

Although SHM looks to be a technology and action for the future there is a variety of activities that could be done straight away. This does include activities such as monitoring loads at discrete locations and feed those back into the fatigue evaluation process. With modelling and simulation tools being available digital models can be established which allow for locations of damage accumulation to be determined. Many of our engineering structures allow for large damages to be monitored such as cracks in the range of tens of centimetres or even complete components having been lost. With a few sensors placed at the appropriate locations those damages could be reliably monitored with immediate action. Furthermore maintenance processes can be simulated which allow the value of SHM potentials to be determined. This will all lead to an automated process delivering the mainly delivered statement of ‘no failures found’ and will allow the human being to concentrate on understanding the true failures only in the end, giving the complete inspection the appropriate intellectual value.

6.0 ACKNOWLEDGEMENT

The author is grateful to inputs provided from Mr. Bernd Frankenstein and Dr. Bianka Weihnacht from Fraunhofer IKTS, Dr. Jochen Kurz from Fraunhofer IZFP, Dr. Chen-Ming Kuo and Mr. Chung-Hsin Kuo from Saarland University and Dr. Herbert Friedmann from Wölfel Beratende Ingenieure.

7.0 REFERENCES

[1] Kapoor H, C Braun and C Boller, 2010: Modelling and optimisation of maintenance intervals to realise Structural Health Monitoring applications on aircraft; Proc. of 5th European Workshop on Structural Health Monitoring.

[2] Kelton D., Sadowski P. and Sadowski A., 2002: *Simulation with Arena*, McGraw-Hill.

[3] Boller C, F.-K. Chang and Y. Fujino (Eds), 2009: *Encyclopedia of Structural Health Monitoring*; Vols. 1 – 5, John Wiley & Sons, Chichester/UK.

[4] Boller C, 2009: Structural Health Monitoring—An Introduction and Definitions; in Boller C, F.-K. Chang and Y. Fujino (Eds): *Encyclopedia of Structural Health Monitoring*; Vol. 1, pp. 1-23, John Wiley & Sons, Chichester/UK.

[5] Labourdette R and O Sensburg (Eds), 1993: *Smart Structures for Aircraft and Spacecraft;* AGARD CP-531.

[6] Boller C and R Dilger, 1993: In-flight Aircraft Structure Health Monitoring Based on Smart Structures Technology; AGARD-CP-531 [5], Paper 17.

[7] Tutton P A and F M Underwood, 1993: Structural Health Monitoring Using Embedded Fibre Optic Sensors; AGARD-CP-531 [5], Paper 18.

[8] Blaha F A and S L Mc Bride, 1993: Fiber-Optic Sensor Systems for Measuring Strain and the Detection of Acoustic Emission in Smart Structures; ibid, Paper 21.

[9] Boller C (Ed.), 1996: *Smart Structures and Materials: Implications for Military Aircraft of New Generation;* AGARD-LS-205.

[10] Boller C, 1996: Fundamentals on Damage Monitoring; in [9], Paper 4.

[11] Kudva J N, A J Lockyer and C B Van Way, 1996: Structural Health Monitoring of Aircraft Components; ibid, Paper 9.

[12] Buderath M., 2009: Fatigue Monitoring in Military Fixed-wing Aircraft; in Boller C, F.-K. Chang and Y. Fujino (Eds): *Encyclopedia of Structural Health Monitoring*; Vol. 4, Chapter 97, John Wiley & Sons, Chichester/UK.

[13] Molent L and J Agius, 2009: Agile Military Aircraft; ibid, Chapter 98.

[14] www.acellent.com.

[15] Malkin M C, 2009: Flight Demonstration of a SHM System on a USAF Fighter Airplane; in Boller C, F.-K. Chang and Y. Fujino (Eds): *Encyclopedia of Structural Health Monitoring*; Vol. 4, Chapter 99, John Wiley & Sons, Chichester/UK.

[16] Meadows L, S Reed and M Duffield, 2009: Operational Loads Monitoring in Military Transport Aircraft and Military Derivatives of Civil Aircraft; ibid, Chapter 100.

[17] Buderath M, 2009: Unmanned Aerial Vehicles; ibid, Chapter 101.

[18] Pipe K, 2009: Health and Usage Monitoring Systems (HUM Systems) for Helicopters: Architecture and Performance; ibid, Chapter 102.

[19] Le D D, 2009: Experience with Health and Usage Monitoring Systems in Helicopters; ibid, Chapter 103.

[20] Galea S C, T Trueman, L Davidson, P Trathen, B Hinton, A Wilson, T Muster, I Cole, P Corrigan and D Price, 2009: Aircraft Structural Diagnostic and Prognostic Health Monitoring for Corrosion Prevention and Control; ibid, Chapter 112.

[21] Salvino L W and M D Collette, 2009: Monitoring Marine Structures; ibid, Chapter 142.

[22] Fritzen, C.-P., P Kraemer and I Buethe, 2013: Vibration-based Damage Detection under Changing Environmental and Operational Conditions. Advances in Science and Technology, 83, pp 95-104.

[23] Golabi K, P Thompson, W Hyman, 1993: Pontis: a network optimization system for bridge improvements and maintenance Technical manual. Publication number FHWA-SA-94-031: US Department of Transportation, Federal Highway Administration.

[24] Kuo C-H , A. Leber, C.-M. Kuo, C. Boller, C. Eschmann, J. Kurz, 2013: Unmanned robot system for Structure health monitoring and Non-Destructive Building Inspection, current technologies overview and future improvements; Proc. of 9th Internat. Workshop on Structural Health Monitoring, DEStech Publ. Inc.

[25] Stoppel M, 2011: Differenzpotentialfeldmessung in der automatisierten Prüfung von Stahlbetonbauteilen; BAM Dissertationsreihe Band 75, ISBN 978-3-9814281-5-5 (in German).

[26] Wenzel H (Coordinator), 2013: Industrial Safety and Life Cycle Engineering (IRIS) – Technologies, Standards, Applications; Vienna Consulting Engineers (VCE); www.vce.at.

[27] Wenzel H, R Veit-Egerer and M. Widmann, 2013: Life Cycle Analysis Applied to the New Jersey Case Study; ibid, pp. 443 – 464.