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INVITED PAPER

In-situ structural integrity monitoring based on non-destructive testing principles

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Abstract

Nondestructive testing (NDT) is the major source of material and structural information to be obtained on a non-invasive basis where different physical principles are applied. This article specifically elaborates on acoustic and electromagnetic principles which have been used for stress as well as damage monitoring in materials and structures. Different successful application examples are described and discussed. A second part of the article then discusses the options those NDT techniques have in being used in the context of structural health monitoring (SHM) and what other sensing options have to be considered with SHM. The pros and cons of the different approaches are highlighted and the importance of numerical simulation for SHM systems is specifically underlined.

1 Structural integrity and damage tolerance

As long as mankind has been realizing engineering structures that had to last and hence not to disintegrate, it has been following the same principle. Starting from an objective or a mission, loads have to be carried for which an engineering structure has to be shaped. This shape is defined by geometric constraints as well as aesthetics and cultural traditions and is a major boundary condition defining the engineering structure's inherent feasibility. Associated with this geometry is the material to be selected since it is the structure's load applied to the shape of that structure which leads to the stresses applied. The stresses applied have to be withstood by the stresses the material is allowed to withstand and it is only when this criterion is fulfilled that structural integrity can be guaranteed. If this is not the case then at least one or even more of the three elements in the loop such as load, geometry and material have to be altered such that the condition of *applied stress* < *allowable stress* is fulfilled (Figure 1).

There are a variety of ways in which this condition can be proved and, hence, met. A simple one is by "trial and error". However, most of the engineering validation today is done by calculation and as a consequence, simulation. Although there is a great deal of knowledge gained in engineering, there is still a large number of unknowns and uncertainties which have to be covered by the well-known "engineering safety factors". These factors are based on engineering judgement and may be rather more conservative other than less, and will have implications on a structure's weight, size and, hence, geometry.

A crucial point in this regard is the knowledge of the structural material's properties in terms of strength and toughness. Another one is the distribution of stresses (and strains) or the material's properties as such throughout the structure itself. With this information, the condition of *applied stress* < *allowable stress* can at least be validated at

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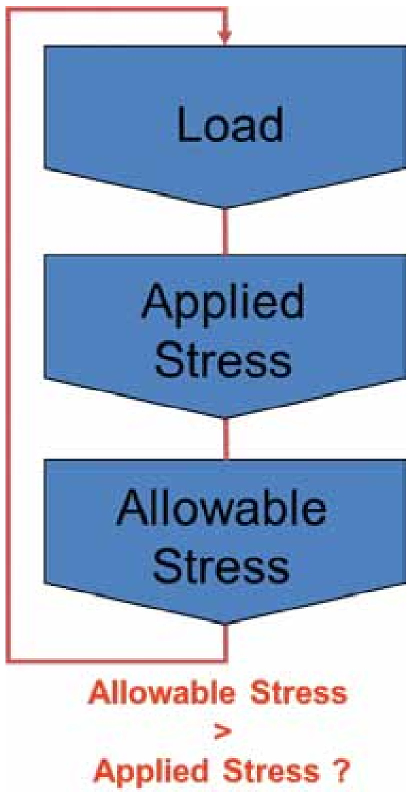

Figure 1. The structural integrity design principle.

the onset of a structure's operational life. However, there are still a large number of uncertainties remaining which do include the true operational loads being applied and the resulting change in the materials' properties as a consequence of the loads applied, which is also considered as ageing or the materials' degradation.

Structural degradation is a consequence of structural loads being applied and is associated with damage in the material and, hence, in the structure. This raises another point of concern and uncertainty that can be expressed by: "How much damage can my structure tolerate?". Not answering this question leads us to exclude any damage that is visible and, hence, detrimental to the material's strength. The occurrence of such a damage is the consequence of repeated loading and, hence, a function of time. This is reflected in the fatigue life curves shown schematically in Figure 2. A set of components will be fatigue-loaded under the same conditions and will result in fatigue lives expressed as load cycles varying easily by a factor of two or more. These tests can be run at different load levels and will result in the fatigue life diagram shown in Figure 2. This diagram can be principally divided into three sections where: a) no component has fractured, b) components fracture and c) all components have fractured.

Whenever a structure is considered to be exposed to damage, it is not allowed to exceed its operational life beyond the number of cycles provided in "zone a" on Figure 2 irrespective of the fact that it is not damaged and may still last longer. This is what is then also termed to be "safe life design". If ever the residual life of the component should be taken advantage of, then further measures have to be taken such that the damage likely to occur can be controlled. In that context, it has to be kept in mind that the abscissa of the fatigue life curve is plotted in a logarithmic scale, hence the fatigue lives (zone b) may scatter significantly. Therefore, if the aforementioned component is run until its true fracture life and, hence, beyond the point where it had to be removed under safe life design conditions, then it may have lasted an additional number of fatigue cycles, possibly the same number as it would have lasted under a safe life design. Allowing a component to be run up to fracture, however, requires an understanding of the damage mechanisms within the component and inspecting the component at well-defined intervals. This is called "damage-tolerant design". Damage-tolerant design allows a structure to last longer, or if this is not desired, to apply higher stresses, which results in a lighter-weight design. Aeronautics has specifically taken advantage of the latter, which has now become standard, specifically in commercial aviation. Damage tolerance – although possibly not directly expressed that way – is however also considered in the context of infrastructure such as buildings as well as heavy machinery. The motivation for such considerations is mainly driven through the increasing effect of ageing infrastructure and what can be done to better take advantage of the potential of this infrastructure's residual life and the infrastructure's assets as such.

The idea of damage-tolerant design can also be extended to engineering structures in general. In that case, a component in a structure may fail if neighbouring components are able to take over the loads in the sense of a redundancy. Therefore, the structure with the resulting fracture may even be controllable under these circumstances. This is generally known as *fail safe design*. If microcracking is not considered to impair the

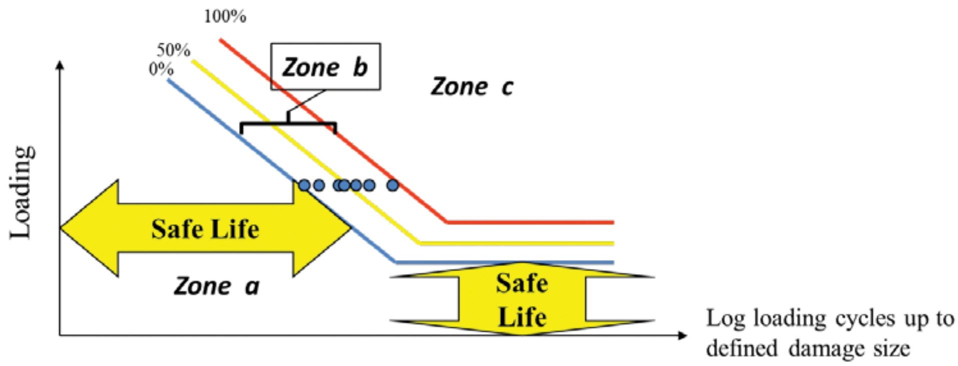

Figure 2. Scatter in S-N curves and the impact on structural design principles.

structure's integrity, then damage tolerance starts from where a crack can be reliably observed and damage progression can be controlled until a tolerable damage constellation within the fail safe area defined by structural design is achieved, as shown in Figure 3 left. Since fracture is a stochastic process it is unlikely that a critical crack may be observed after a defined inspection interval of Delta N/2. It may be much more likely that no detectable crack may be observed after this interval. If this is the case, which is considered as "no failure found", then the assumption of the crack starting at the detectable crack length can be started again and the procedure is repeated as many times until a crack is found that is larger than the defined *detectable crack* but definitely smaller than the *critical crack length.* This procedure is shown schematically in Figure 4. Once such a crack (damage) is observed repair has to be done irrespective of how far away the crack is from the critical crack length (or size). If a repair is performed and the respective component is not fully replaced, then the repair itself may even become an object of enhanced damage tolerance observation and hence monitoring. This is specifically true for repairs which do not allow the original state of structural integrity to be established.

Dealing with damage tolerance requires the respective tools to be available. This starts with a structural strength analysis based on FE modelling which allows stress and strain distributions to be determined within the structure based on the external loads being applied. A fatigue life evaluation tool may further allow the fatigue damage being generated to be calculated, and to determine at which of a component's structural locations, damage is likely to accumulate. These locations being very often notches or stress concentrations in general, are then the locations to concentrate on from a risk-based inspection and hence damage tolerance point of view.

The damage to be tolerated is a crack of a defined size, which is either defined as a fatigue life damage criterion or as fracture mechanics.

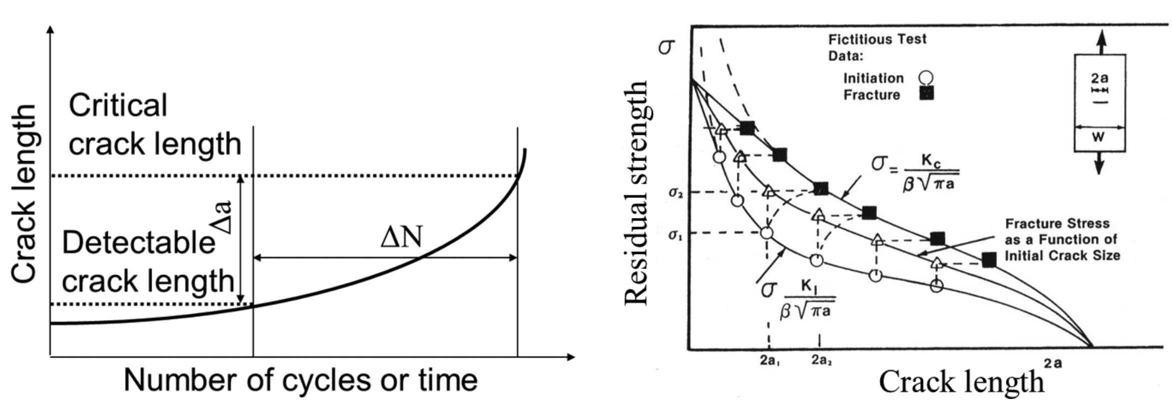

Figure 3. Crack growth (left) and residual strength (right) as key parameters for crack propagation based fatigue life assessment.

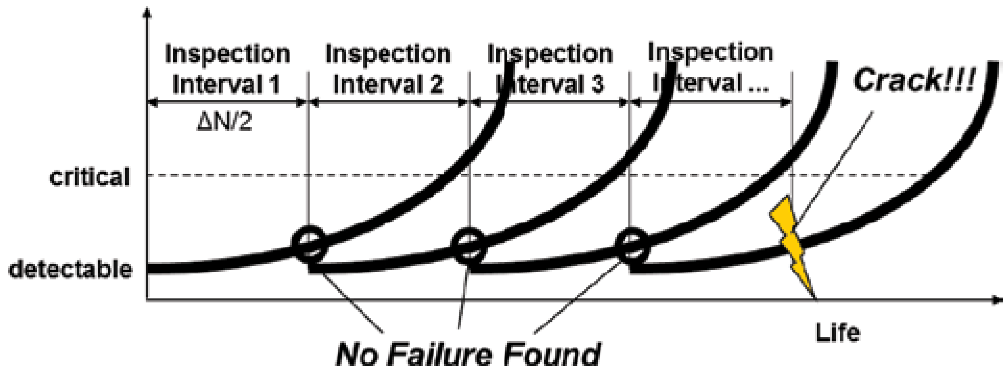

Figure 4. Crack propagation, inspection und damage tolerance principles.

In both of the cases fracture mechanics data are required to allow the residual life to be determined in terms of crack propagation life. This residual life determination has to start at least when the safe life period is over and fracture is likely to occur. Due to the stochastic nature of fatigue, it is most likely that the predicted inspection interval will be exceeded and the inspection interval prediction will have to be repeated several times. With each of those predictions usually based on linear elastic fracture mechanics, an initial crack length has to be assumed. The size of this crack length is defined by the means of non-destructive testing (NDT) and must provide a probability of detection of mainly 100%. This is where NDT comes into the design process, being not just an instrument to guarantee a material's and structure's quality during manufacturing and assembly only, but also to guarantee a structure's integrity during its operational life and, specifically, when a structure is considered to be used beyond its operational design life. With structures having been designed damage tolerant, the application of NDT has been designed in. However, the challenge starts with those structures where this has not been designed in and which exist today and where NDT suddenly becomes an integral part of their operational life without having been designed in initially.

2 Nondestructive testing

Nondestructive testing (NDT) can comparatively still be considered as a relatively young science. It is based on the physical principles to be used to assess materials and structures on a non-invasive basis. The principle used in around 95% of the cases is visual, starting from a human being's trained eyes and skills over a variety of visualization aids such as magnifying glasses, microscopes or endoscopes respectively. This, however, only allows a material and structure to be inspected from its surface. The more interesting part comes when NDT methods even allow an observation below the surface. This is, indeed, possible when looking at the wide scope of vibrations, acoustics, electromagnetics, radiography and temperature based principles. Of all of those, the acoustics and electromagnetics-based principles are possibly the ones known best and hence used most.

Besides looking for damages, such as cracks, NDT is even able to determine the geometric dimensions of changing material conditions such as hardening depths or coatings. It is further able to determine stress conditions specifically in metallic structures, and this even at various scales. The following sub-chapters and paragraphs will therefore highlight a few applications of interest starting with acoustic principles first and considering electromagnetic principles next.

3 Acoustic principles

Using acoustics for NDT is mainly associated with ultrasound using piezoelectric transducers coupled to the structure to be inspected and emitting an ultrasonic signal by one transducer that is recorded by another (pitch-catch) or recording the signal by the same transducer (pulse-echo). Another way of generating ultrasound in a ferromagnetic material is by electromagnetic transduction where the Lorentz forces generated through an alternating electromagnetic current in a superimposed static magnetic field will induce ultrasonic waves in accordance with the direction of generation. Recent developments in ultrasonics are mainly associated with the application of phased arrays as well as with the enhanced processing of transducer signals received, such as with the use of the synthetic aperture focussing technique (SAFT) [Schmitz *et al.* 2000]. SAFT principally allows the orbits of a reflector within a structure to be superimposed such that the location and reflecting signal of the reflector is significantly enhanced. The ability to store a large amount of sensor signals and to get those processed in close to real time has allowed SAFT evaluations to be further optimized in accordance with a procedure named full matrix capture [Holmes *et al.* 2004] or sampling phased array [Bulavinov, 2005]. This approach sees that signals for all transducer combinations on a phased array are stored in a database. It amounts that those signals can then be back-propagated to the position/shape of the detected reflector by arbitrarily phase shifting in a computer in accordance with a SAFT process such that a best resolution image is obtained due to the refocusing of the signals.

4 Ultrasonic based stress measurement in metallic structures

There is a clear correlation between ultrasonic time of flight (TOF) and stresses allied to a structure as well as to the elastic constants. Those can be measured when the respective geometry to be inspected as well as some reference parameters are known. It is obvious that when a structure is exposed to a load and, hence, stress, respectively, it will change in length in the direction of the load. With this, a change in TOF of an ultrasonic signal can be principally observed. Hence, when tension is applied, this leads to an increase in TOF or a reduction in wave propagation speed. However, when being compressed, a reduction in TOF or an increase in ultrasound velocity is observed. This is not limited to longitudinal waves only, but can also be applied to transversal and hence shear waves. To further determine a material's properties, there is a correlation between a material's density, the elastic constants and the various acoustic wave speeds, where the number of elastic constants depends on the type of crystal structure and can generally be expressed in a symmetric 6×6 stiffness matrix. Depending on the material considered, the number of independent elastic constants reduces to two as in the case of an isotropic material. Further details related to ultrasonic based stress measurement can be found in [Schneider, 1999].

This option in ultrasonic testing allows for a variety of different stress related phenomena to be measured. In [Schneider *et al.* 2012] stress measurements in rebars have been reported where the velocities of a shear wave determined can be seen in Figure 5. Although showing a large scatter in the data recorded, there are some clear areas that can be determined from averaging the velocity signal which indicate a general velocity change. These changes are a consequence of the loads applied to the rebars being an indicator for the

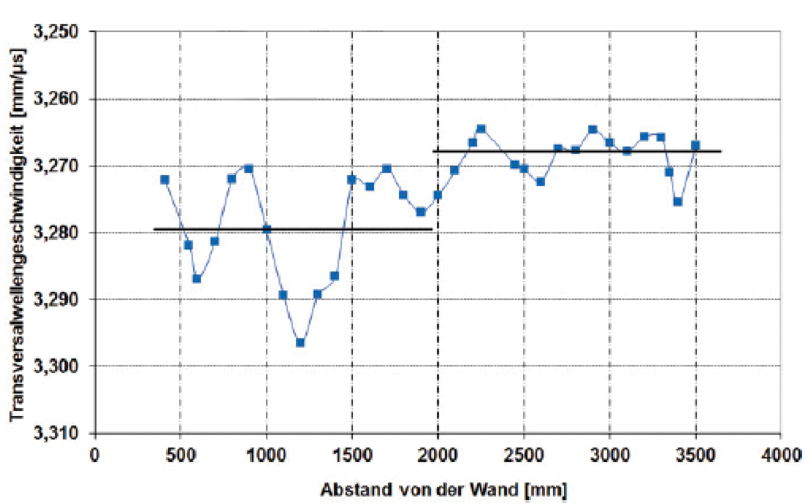

Figure 5. Velocity of a shear wave polarized along the length of a rebar [Schneider *et al.* 2012].

loading condition applied onto the rebars and, hence, the reinforced concrete structure as such.

Another interesting effect where ultrasonic stress measurement is successfully applied is the measurement of the correct torque momentum on pre-stressed screws. This pre-stress applied is usually determined from the torque momentum applied to the screw. However, this does not result only from the pre-stress in the screw, but also includes forces resulting from friction between the screw and the component, which do not have an influence on the screw's pre-stress at all. An alternative to purely measuring a screw's pre-load and hence pre-stresses exists by measuring TOF within the screw. The measuring principle uses the systematic change of the ultrasonic TOF with increasing application of torque and, hence, of tensile stress. With increasing tensile stress, the screw elongates (elastic strain) and the sound velocity decreases intrinsically due to stress (acousto-elastic effect). The relationship between TOF and applied stress is either calculated using the elastic constants of the screw material, or it is calibrated in a controlled fastening experiment. A commercial ultrasonic transducer is incorporated into the wrench socket and the ultrasonic TOF is measured with rates up to about 80 Hz. The measured TOF values are continuously compared with the reference TOF value where the TOF measured corresponds to the stress state given by the requested clamp load and the known screw diameter. As soon as the TOF defined is reached, the system stops the fastening process. Figure 6 displays on the left hand side some details of the module developed by Fraunhofer IZFP which is a system to be adaptable to almost every commercial pulse screwdriver. Some commercial screwdrivers allow the reading of the applied torque. The combined presentation of applied torque and ultrasonic TOF is very helpful in controlling the quality of the fastening process.

Figure 7 displays a perfect match in fastening characterized by the similar change of both the applied torque and the time-of-flight.

In case TOF increases more when compared to the torque per time unit, the screw used has a lower strength value than expected. In case torque increases more than TOF per time unit, then an increase in friction is indicated. A three months study of an in-field application yielded reproducibility and accuracy of the process being better that ± 4% [Schneider *et al*. 2006].

5 Ultrasonic based analysis of dissimilar welds

The welding of austenitic steels faces a significant challenge due to the fact that the resulting welds show a significant dendritic structure, which also results in a significant anisotropic behaviour of the weld. Ultrasound based inspection of those welds leads to a skewing of the ultrasound signal which results from the material's anisotropy. Getting the trail of the ultrasound signal described accordingly therefore requires the following information to be available: a) type of crystal structure, b) elastic constants of the crystal, and c) position/orientation of the dendrites. An approach on how to accordingly inspect dissimilar austenitic welds based on ultrasonic testing has been described in [Pudovikov *et al*. 2011; Pudovikov, 2014]. The approach applied is schematically shown in Figure 8. It starts from acquiring data (step I) using a phased array probe and applying the sampling phased array approach. In the specific case applied here, the orientation of the dendrites in the weld had been assumed

Figure 6. Schematic of the Fraunhofer IZFP module for the on-line measurement of the clamp load and to control the fastening process (left) and a commercial screwdriver with Fraunhofer IZFP module (right).

Figure 7. Screen shot of the GUI of Fraunhofer IZFP system showing applied torque (yellow) and ultrasonic time-of-flight (blue) versus processing time of the fastening process with respect to good fastening process.

postulating that a defined welding process will generate a fairly clear orientation of the dendrites. Since the resulting crystals are of a transverse isotropic hexagonal nature the five elastic constants C_{11}, C_{13}, C_{33}, C_{44}, and C_{66} are the unknowns which have to be determined. This is achieved through a ray tracing-based iterative simulation process (step II) such that the reconstruction of an artificial reflector with a well-known position and size (step III) is optimally achieved. Through a sector-scan analysis (step IV) the quality of the result of iteration and hence the simulation is assessed and iterative adjustments of the elastic constants are made in case the optimum of the iteration process is still not achieved (step V). Once the optimum is achieved, the correct values of the elastic constants are obtained. The procedure used has been named the iterative gradient elastic constants descent method (GECDM). Figure 9 shows a result with this approach where cracks generated at the interface between weld and host material have been clearly identified.

6 Materials characterisation with electromagnetic ultrasonic transducers

That stress conditions as well as possibly others can be measured using electromagnetic transducers (EMAT) along a fatigue test has been shown in a series of experiments of which the test set-up is shown in Figure 10 [Seiler *et al*. 2013]. EMAT induced ultrasonic waves have been sent through the un-notched specimen shown during low and high cycle fatigue tests performed at 300°C and amplitudes and times of flight (TOF) have been measured. Figure 11 shows some result as an example where the stress amplitude recorded in a strain controlled test of an austenitic stainless steel material is compared to the amplitudes and TOF measured during the fatigue test and where a good correlation can be observed between those parameters. These results are a further proof that ultrasound can be well used to stress condition characterisation within a metallic

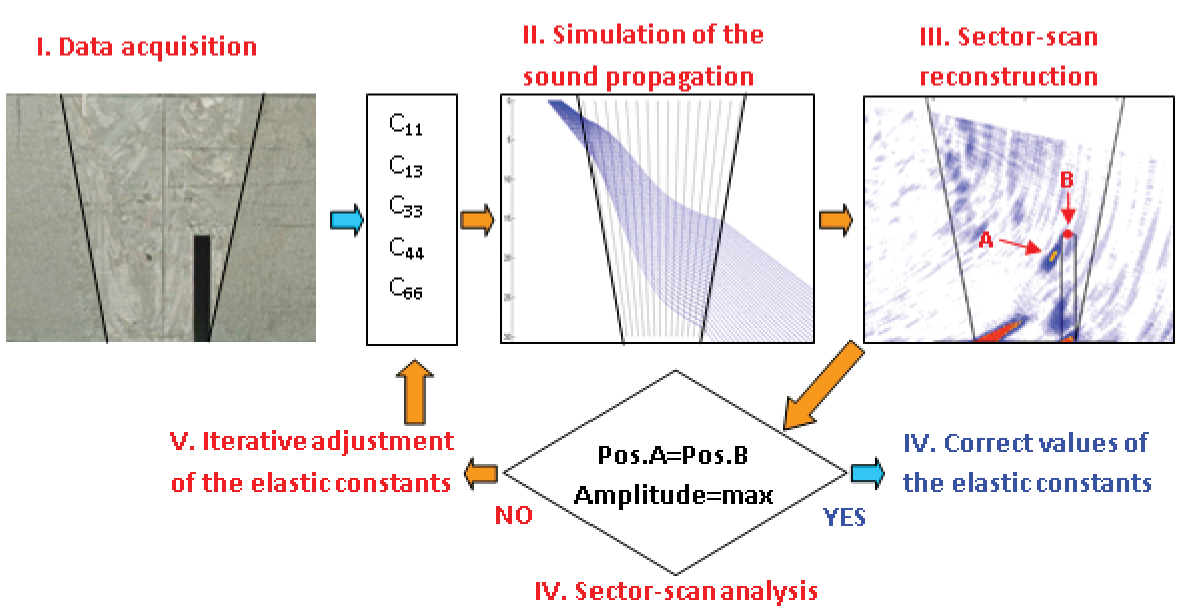

Figure 8. Iterative gradient elastic constants descent method.

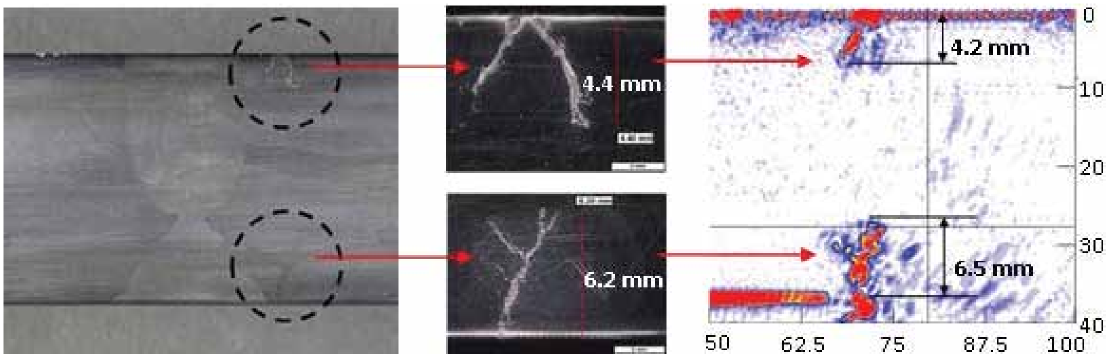

Figure 9. Direction dependency of the phase and group velocities on the phase and group angles in a transverse-isotropic medium.

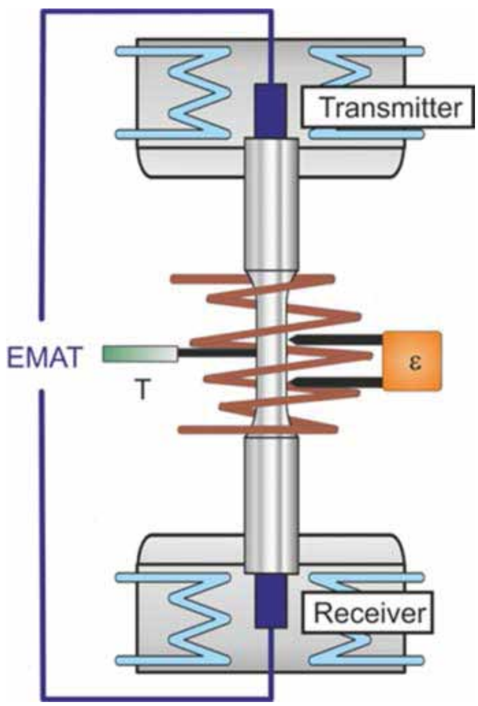

Figure 10. Experimental setup for fatigue tests with an extensometer for strain-stress hysteresis measurements (ε), thermocouple (T) for setting and controlling the test temperature and EMATs.

material and possibly even more with regard to any damage precursors being inherent to a ferromagnetic material due to its ferromagnetic properties and their changes by fatigue.

7 Materials characterisation with micromagnetic techniques

The early detection of degradation phenomena can be one of the striking advantages with NDT. Those are required when microstructural changes such as those occurring in steel components of pressure vessels and pipes have to be revealed. Micromagnetic NDT based on a dynamic periodic local magnetization of the material and observed as a hysteresis loop is especially sensitive to microstructural changes during a period when generation and multiplication of dislocations, development of precipitations, generation of vacancies and micro voids, and possibly others being the nature of an ageing metallic material do prevail. There are many correlations between dislocation movement under mechanical loading and the movement of the micromagnetic mechanisms – such as the Bloch walls in iron-based steel materials – under magnetic loading, i.e. when a material is magnetized. Dislocation and Bloch wall movement, both, are governed by temporarily pinning at lattice defects in the microstructure. Barkhausen noise (BN) measurements and the higher harmonic analysis of the magnetic field are techniques based on irreversible magnetization processes and non-linear hysteresis phenomena. The measurement of the incremental permeability ($\mu\Delta$) and the dynamic, also called incremental magnetostriction (E_λ) are based on reversible magnetization process realizations [Dobmann *et al.* 1998]. Magnet-inductive coils (passive, BN; active, incremental permeability), Hall-effect elements and GMR (Giant Magnetic Resistors) are used as sensors to measure the magnetic field while EMAT (Electromagnetic Acoustic Transducers) are used to sense the dynamic magnetostriction. Figure 12 illustrates the measurement principle. To generate the magnetic field excitation of a component to be inspected, a u-shaped yoke is used in addition to

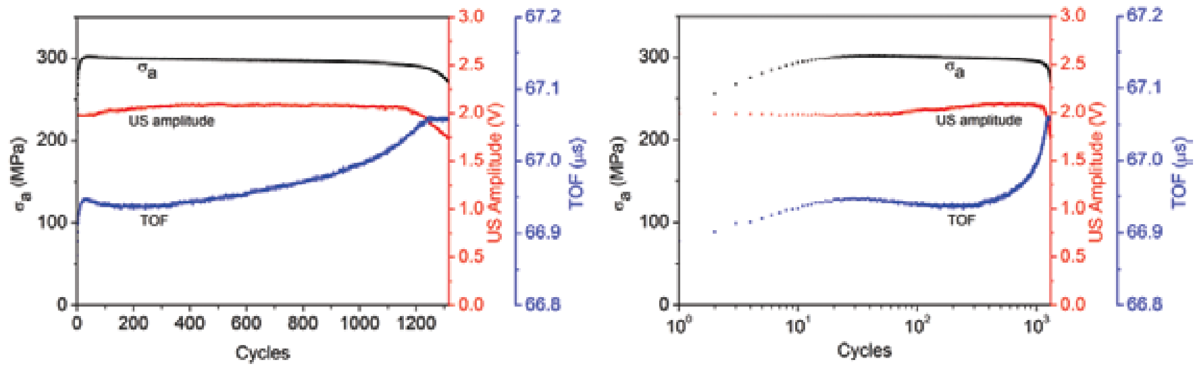

Figure 11. EMAT based ultrasonic measurement results compared to stress amplitudes in a strain controlled fatigue test. Left: linear plot; right: logarithmic plot. Note the higher sensitivity of TOF.

the sensors, the driver hardware and the adapted signal interpretation software.

The low-alloy, heat-resistant steel 15 NiCuMoNb 5 (WB 36, material number 1.6368) is a steel widely used as a material for pipes and vessels in boiling and pressurized water reactor nuclear power plants. Damage has specifically been observed when the operating temperature was between 320° and 350°C [Altpeter *et al.* 1999] where an operation-induced hardening associated with a decrease in toughness (–20%) has been seen in all cases. This change could be proven by NDT using the 3MA (Micromagnetic, Multiparameter, Microstructure and stress Analysis) system developed at Fraunhofer IZFP [Altpeter *et al.* 2002.1]. The 3MA-approach can be described as the solution of an inverse problem where micromagnetic parameters are measured and target quantities such as mechanical hardness, hardness depth, yield strength, tensile strength, impact energy along a Charpy V-test, ductile to brittle transition temperature and others are predicted by regression or pattern recognition algorithms.

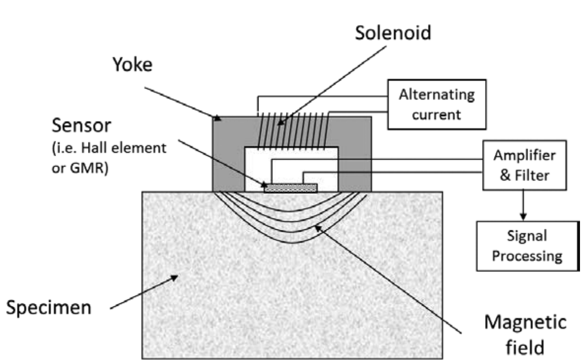

Figure 12. Micromagnetic material characterization, measurement set-up.

One example that documents the analogy between mechanical and magnetic hardness (H_{co}, coercivity) is shown in Figure 13. The Cu-rich WB36 steel is specified to be composed of between 0.45 and 0.85 mass% Cu (in average 0.65%). Half of this Cu is still in a solid solution and can precipitate when the material is exposed to service temperatures. This process is shown as a result in Figure 13 where the resulting degradation is observed as a hardness increase over time achieving a maximum and then dropping again. Combined with low-temperature creep, this has led to a situation where pipes have badly fractured such as the example shown in Figure 13. A comparison to 3MA measurements shows that this behaviour can also be observed when looking at the development of coercivity derived from the non-linear analysis of the magnetic field (H_{co}) and that this could easily be used as an indicator for monitoring purposes. It should be mentioned here that the degradation process is enhanced when fatigue is superimposed on a thermal exposure [Dobmann, 2011].

8 Impedance based materials characterisation

Electromagnetic impedance can be measured in a variety of different ways. One of them is by giant magneto resistors (GMR), which have been associated more with computer hard drives than with NDT sensors. However, their small size, being only in the millimetre range, makes them highly attractive to be used in locations difficult to access from a geometry's point of view. The parameter measured is impedance, and there have been different experiments performed where impedance has

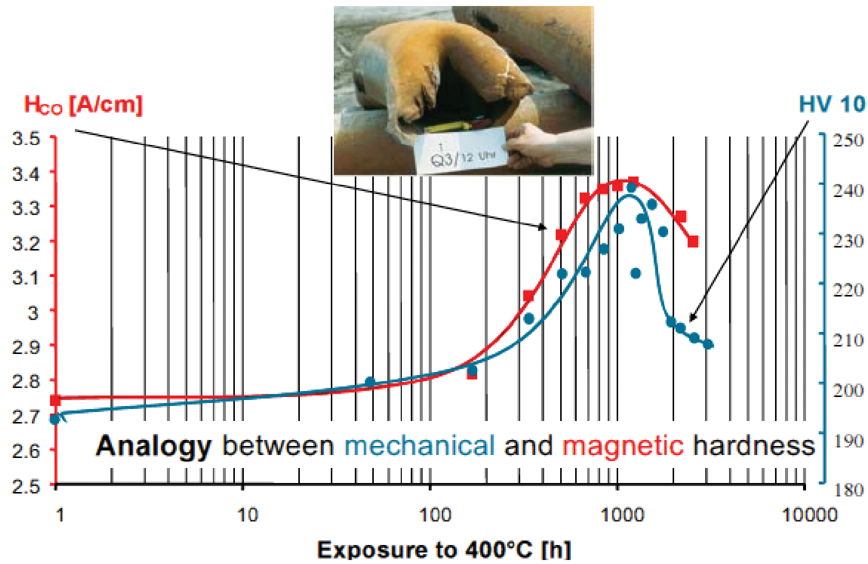

Figure 13. Mechanical and magnetic hardness of degraded WB36 specimens.

been well correlated to local plastic strains. Impedance is a major parameter characterising damage and damage accumulation at a sub-microcrack and hence microscopic level [Starke, 2007; Nebel *et al.* 2003]. Figure 14 shows some results obtained from [Starke, 2007] for a constant amplitude fatigue test and from [Bassler, 1999; Lang, 2000] for a variable amplitude test where, in both cases, the clear correlation with plastic strain can be observed. These correlations are currently subject to some further research work.

9 Implications of NDT on structural health monitoring

Structural health monitoring (SHM) is considered to be the integration of sensing and possibly also actuation devices onto or into materials and structures to allow the loading and damaging conditions of a structure to be recorded, analysed, localised and predicted in a way that NDT becomes an integral part of the structure. The integration of sensors and, possibly, also actuation devices has been performed to a limited extent over the past decades in engineering. The sensor type having possibly been integrated most in that regard is resistivity based electrical strain gauges, mainly for monitoring strains and, hence, loads being applied to the structure. A type of sensor also being considered is accelerometers used to determine dynamic loads from the accelerations being measured. It is only since a little more than the last two decades that even other types of sensors have attracted the interest of the engineering and structural designing community. This has been mainly driven by

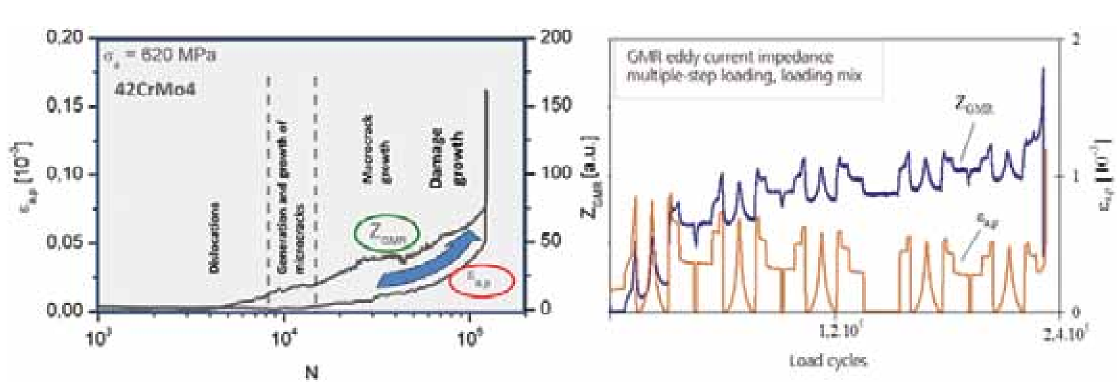

Figure 14. A comparison between plastic strain and GMR measured electromagnetic impedance obtained on a constant amplitude fatigue test [Starke, 2007] (left) and random amplitude test [Bassler, 1999; Lang, 2000] (right).

the increasing use of fibre reinforced composite materials such as CFRP where the monitoring of structures made from those materials has become focal. One of the motivations in that regard has been the fear that so-called barely visible impact damages (BVID) could be generated from impact loads that would not be visible from the structural outside when compared to a similar impact event happening to a metallic structure where a dent on the structure would be observed. A further motivation in that regard has been the question of how a composite materials structure could even become damage tolerant. In the early days of CFRP the material was considered to not demonstrate fatigue at all, which also excludes the consideration of damage tolerance. However, in recent days, fatigue in composite materials is a viable issue to discuss and it is there where SHM and damage tolerance again come into play. The lack of sufficient knowledge in damage mechanics and damage progression in composite materials when compared to metals, and the comparatively easier possibility of integrating sensing and, possibly, also, actuation devices into the structural material has encouraged composite materials being developed to a 'smart' material.

SHM is, however, not limited to one of the core fields of NDT only, being materials characterisation and flaw detection traditionally. SHM also encompasses the wide field of loads monitoring, which is a precursor for structural assessment from a structural mechanics as well as from a prognostics point of view. Whenever a structure is due to be equipped with sensors beneficially the ground rule has to be: *Maximize a SHM system's efficiency by minimizing the number of sensors required to only the most efficient ones.* Loads monitoring is a strong contributor to this because it only requires a few sensors to be available if the structure considered is FE modeled. The load information monitored can be directly fed back into the FE model and the damage accumulated can be calculated for each of the structural elements. This, then, does allow the locations to be determined where damage accumulates most, these being the locations where detailed damage monitoring is required and sensors have to be placed additionally. Additional load monitoring sensors may further enhance the prognostics of damage accumulation gradually if the loads are monitored in locations where FE-modelling becomes a challenge.

The various technologies being applied in the context of SHM have been summarized in [Boller *et al.* 2009]. The types of sensors being considered here are optical fibers, MEMS and piezoelectric transducers. Electromagnetic sensors have only been considered to a very limited extent. The reason for this limitation is possibly due to the fact that much of the SHM activities have been driven out of a structural dynamics point of view. Fiber optical Bragg grating (FBG) sensors are possibly the most widely considered optical sensors used in SHM which have the advantage that they can be placed at even highly narrow locations, integrated into a composite material and multiplexed along a single fiber. They are prone to any electromagnetic interference and allow for strains as well as vibrations to be monitored even up into the ultrasonic frequency range. Pressure and temperature are further structural impacts that can be measured with FBGs as well. Even chemical processes may be monitored such as resulting from corrosion if the fiber is coated with a corrosion sensitive coating. In operation, FBG sensors have been proven to be rugged and to operate over a long period of time. Principally, FBG sensors have been proven to be specifically suitable for loads monitoring, be those loads mechanical or even environmental.

MEMS in SHM have been mainly considered as vibration and, possibly, also as corrosion or environmental monitoring sensors in general. However, when compared to the other types of sensors described here, their application has been rather limited. Furthermore, MEMS hasn't played any significant role in NDT so far.

The transducer most widely used in SHM, and possibly also NDT, is based on piezoelectric materials. The reason for this may be that it can be used as a sensor as well as an actuator. The frequency range where it can be operated is wide starting from a few Hz and going up into the MHz range. This allows a conventional modal analysis to be performed as well as ultrasonic testing. A field where the latter is very much considered from a sensing point of view is acoustic emission, with successful work having been reported such as in [Schulze *et al.* 2010]. However, signal processing in acoustic emission may become laborious and signals may only be generated when high loads occur which can be rare in the case of in-service loading. The advantage of a piezoelectric transducer also being able to act as an actuator is that it can emit vibrations and hence acoustic signals and can be operated like an ultrasonic transducer. However, when compared to conventional ultrasonic testing, a major disadvantage of the SHM based transducer is, that due to its integration into a structural component, it becomes stationary and the number of data sampling options is therefore rather limited. This limitation has led acoustics based SHM research to increasingly look into guided waves where structure inherent eigenfrequencies allow an acoustic wave to disperse through the structure in an optimum way with regard to the energy input made. However, the phenomenon of guided waves is limited to a constant geometry, and whenever the geometry changes, the eigenfrequency generating and propagating the guided wave changes as well. The generation and understanding of guided waves travelling as well as their interaction with imperfections in structures and the resulting signals monitored has been reported in various books published recently [Rose, 1999; Giurgiutiu, 2008; Su *et al*. 2009; Ostachowicz *et al*. 2012]. Anisotropy in composite materials is a further challenge in the context of guided waves, which is why guided waves based on SHM may be currently much more efficiently considered with an isotropic metallic material.

When trying to inherit experience from NDT into SHM a comparison between NDT related phased array inspection and the sparse array of piezoelectric transducers of a SHM-based monitoring system is a question that arises. That a sparse transducer array based on SHM will not be able to achieve the same quality of result an NDT-based sampling phased array would do becomes obvious when looking at the number of sampling combinations each of the approaches has. While a SHM-based system consisting of *n* transducers has only *n* sampling combinations available, the number of samples in an NDT-based sampling phased array inspection is virtually endless. As such, the higher resolution result is always obtained with the NDT-based approach in that regard, but more time is required for the inspection process. Additional effort may be required with dis- and reassembly of components to get access to the location of interest. To further enhance the benefit of an SHM-based monitoring system and approach requires a concentration on the locations where damage is most likely to occur and to possibly even know which configuration of damage is the only one to be tolerated at the location considered. This will allow a network of transducers to be configured such that it will detect the tolerable damage best. To get this done, simulation is required and it is the importance of the simulation capability, which has to be underlined here. An alternative solution would be to generate a structure with a grid of close to an endless number of transducers where the transducer layer would virtually be a part of the structural material in the sense of a smart material. Getting this realized, however, may be a long way away since the issue of sensor signal processing has not yet been solved, and may, hence, just be a second choice option in terms of an SHM technology solution realization.

A completely different way of monitoring not sufficiently explored in the context of SHM is electromagnetics. Electromagnetics in terms of permeability, electromagnetic impedance, Barkhausen noise and electromagnetic higher harmonic behavior includes phenomena being currently increasingly discovered in the NDT environment as well as in the context of quality assurance in the manufacturing and assembly of engineering components and structures. The sensing systems used today such as the 3MA system [Altpeter *et al.* 2002.2] mentioned before are good examples, which have a potential for significant miniaturization when looking at the potential GMR sensors may have. This is an increasing field of research allowing damage conditions to be determined at a submicron level where SHM could be of significant value when thinking of the large amount of ageing metallic infrastructure with damage conditions being only vaguely known.

10 Conclusions

Although there is a variety of further NDT principles being used such as thermography, radiology or microwaves, there is, currently, only a limited number of NDT principles that qualify for SHM. Besides visual inspection, which has not been expressively discussed here, vibrations and acoustics based NDT techniques are the ones from which SHM takes the largest inheritance at the moment. Still, there is much to be understood from the structural damaging process in a material, as well as from a sensor and actuator signal processing point of view. This understanding can be very much supported by simulation which is a reason why simulation in SHM must attain a much higher significance than it has today. With this, the appropriate transducer configurations for SHM can be tailored and signals can be understood. Which signals need to be seen in the context of damage to be tolerated will allow optimum configurations of transducer networks to be determined which are essential to retrieve the maximum a ‘static’ SHM system may be able to provide.

There are still further options explored in NDT which have not been very much considered in SHM so far. One of them is stress measurement in stressed metallic structures where acoustic principles can be used as well as electromechanical ones. The latter technique also includes the option of damage monitoring at a sub-microcracking level, which no other technique is able to deliver when excluding non-SHM-compatible techniques such as radiography.

It has finally to be concluded that SHM is not just a replacement of NDT in terms of automation of an inspection process, but rather an umbrella under which NDT is linked with many other features of structural mechanics be this loads monitoring, vibration monitoring, stress or fatigue life evaluation analysis, to name just a few. This brings in further parameters to sense and phenomena to simulate which leads to an increasing complexity in an assessment but may also open options of enhanced multifunctionality for the future.

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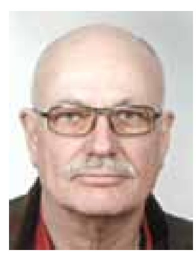

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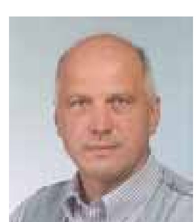

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