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Approaching the assessment of ageing bridge infrastructure

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Abstract. In many of the industrialized countries an increasing amount of infrastructure is ageing. This has become specifically critical to bridges which are a major asset with respect to keeping an economy alive. Life of this infrastructure is scattering but often little quantifiable information is known with respect to its damage condition. This article describes how a damage tolerance approach used in aviation today may even be applied to civil infrastructure in the sense that operational life can be applied in the context of modern life cycle management. This can be applied for steel structures as a complete process where much of the damage accumulation behavior is known and may even be adopted to concrete structures in principle, where much of the missing knowledge in damage accumulation has to be substituted by enhanced inspection. This enhanced and continuous inspection can be achieved through robotic systems in a first approach as well as built in sensors in the sense of structural health monitoring (SHM).

Keywords: ageing infrastructure; structural health monitoring; fatigue; PHYBAL; steel; concrete; inspection robotics

1. Introduction

1.1 Ageing infrastructure life cycle management – a motivation

In many of the highly industrialized countries today a lot of infrastructure has been built when economy has been taking off. In Germany this has been specifically after WW II as it has been happening in a similar way in Japan too. Other countries such as France, the UK, Canada or the USA have accumulated also a large number of infrastructure over the last century or two, although the establishment of their infrastructure may have been spread more evenly over time. All of this infrastructure was built somehow for a vaguely specified period of time which could even be defined as ‘forever’, although when thoroughly checked the assumed life is said to be no more than 100 years. However, nobody truly has made this check or better, this infrastructure said to last for at least 100 years is most likely to last much longer. Much of this infrastructure is even listed which is a definition per se that life can be ‘forever’. In many of the cases the degree of damage of this infrastructure is not sufficiently known because loads have not been clearly recorded and design documents have vanished. However, loads resulting from operation as well as the

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environment may have changed significantly, specifically in the case of bridges, which do make a sufficiently realistic estimation of the damage condition of those structures even more difficult.

All of this ageing infrastructure needs to be managed with regard to its integrity and the question of the damage to be tolerated from a structural integrity as well as from an economic point of view arises. Life cycle management therefore becomes essential and the question is on how to take this approach. Structures being exposed to loads do damage specifically when they exceed a threshold value. Those loads can be mechanical as well as environmental where the two types of load interact in a way that the environmental loads will reduce the threshold of the mechanical loads leading damage to be initiated. Loads applied to structures can be measured in terms of traffic loads, wind, snow, temperature, humidity and possibly more. However, a key question arises what damage those loads cause and what damage is defined to be (crack, delamination, stiffness loss, material loss, etc.). A further question arises as to how damage accumulates as a function of loads over time and when a damage becomes critical. Such an assessment can only be done when:

1. A detectable damage can be defined from an inspection point of view,
2. A critical damage can be defined from a structural integrity point of view,
3. The time for the damage to grow between the detectable and the critical damage condition can be determined.

Such an approach is fairly possible with metallic materials at least to a significant extent. It starts from the fact that damage can be detected by means of nondestructive testing and a tolerable damage can be defined from a structural integrity point of view as well. In metals such as steel damage is widely defined as a crack and with the help of fracture mechanics the time can be predicted how long a damage/crack will take to progress from a detectable to a critical size. This time interval combined with the stochastic nature of damage progression will then determine when an inspection will have again to be made and where a non-critical damage may be found that then will have to be rectified. This is to what extent damage tolerant design is performed in aviation where the objective is lightweight design. However, when lightweight design is less of an issue such as in civil engineering, damage tolerant design can still be of an advantage in terms of extending a structure’s safe operational life.

When it comes to non-metallic structures such as made from concrete the damage tolerance approach becomes more complicated since neither the detectability nor the criticality of damage as well as the way damage propagates as a function of applied loads is known. However, still the damage tolerance approach described for metallic structures can be applied in principle with the difference that many of the damaging phenomena including the damage accumulation process are less known. Damage assessment in concrete structures today is still fairly crude and is mainly based on visual inspection only where an experienced inspector will judge if a structure has to be classified as ‘green’, ‘yellow’, or ‘red’ equivalent to a traffic light system. Neither a quantifiable degree of damage nor a description of damage accumulation exists for concrete structures so far and it is such that only by visual inspection those structures can be assessed today with the additional effect that the experience and hence images gathered can serve as a database to study damage progression as a function of applied loads. Furthermore this procedure does possibly allow the respective mechanisms leading to damage progression in a fairly composite material such as reinforced concrete to be derived.

Civil infrastructures with bridges being a good example are large and hence difficult, risky and expensive to inspect. This prevents those structures to be inspected frequently by human inspectors. However when it comes to damage tolerance of those structures where damage mechanisms are fairly unknown such as with concrete a frequent inspection at least of the locations being damage critical is a must. The solution to this problem can therefore currently only be seen through automation of the inspection process. Throughout the following options for a modern life cycle management of civil infrastructure is described, first for the more established process for steel structures and then for the emerging issue of ageing concrete structures. Principally the processes for the two material types are the same however the achievement for the two different types of material are different which allows gaps for future research initiatives to be identified.

2. Steel infrastructure assessment

Anyone dealing with fatigue knows that fatigue life scatters. This scatter can be a factor of two or even more in fatigue life when it comes to metallic structures where the fatigue behavior such as with the description of crack propagation is comparatively well known. As regards the age of bridges the average age of German railway steel bridges is close to 90 years now with the oldest being 175 years of age (Deutsche Bahn AG). Those bridges may easily last another 100 years in average but this requires more care in monitoring and maintenance and the consideration that a certain degree of damage might be tolerated. Many of those bridges have become landmarks and possibly listed, which has now the endurance of those structures mainly to be infinite. Nobody can therefore consider those structures to be free of damage and the question is: *How much damage can those structures sustain?*

Design concepts of such a nature being called *damage tolerant design* are well known within the context of aeronautics. Damage tolerant design defines a condition of a detectable damage and a tolerable damage respectively (Fig. 1) and allows for a damage progression period ΔN to be calculated for a specific operational load using damage accumulation rules such as elastic or elastic-plastic fracture mechanics in the case of metals. To provide for scatter in damage occurrence an inspection is performed after a period of $\Delta N/2$ and in case no obvious damage is found the process is repeated until damage is identified where the damage found then has to be repaired (Fig. 2).

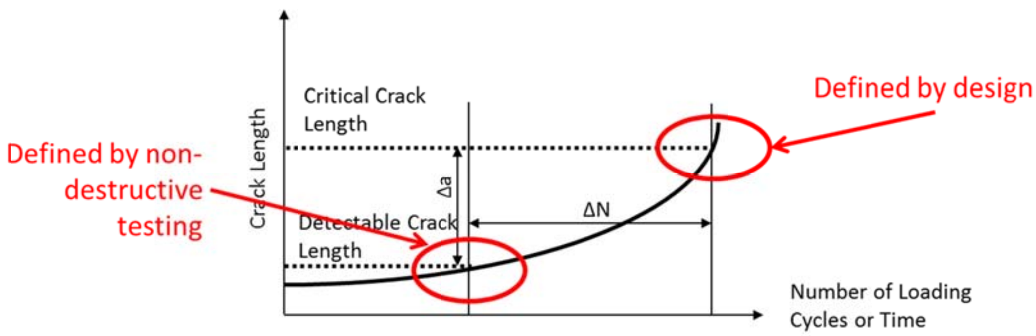


Fig. 1 Definition of damage tolerance limits in damage tolerant design

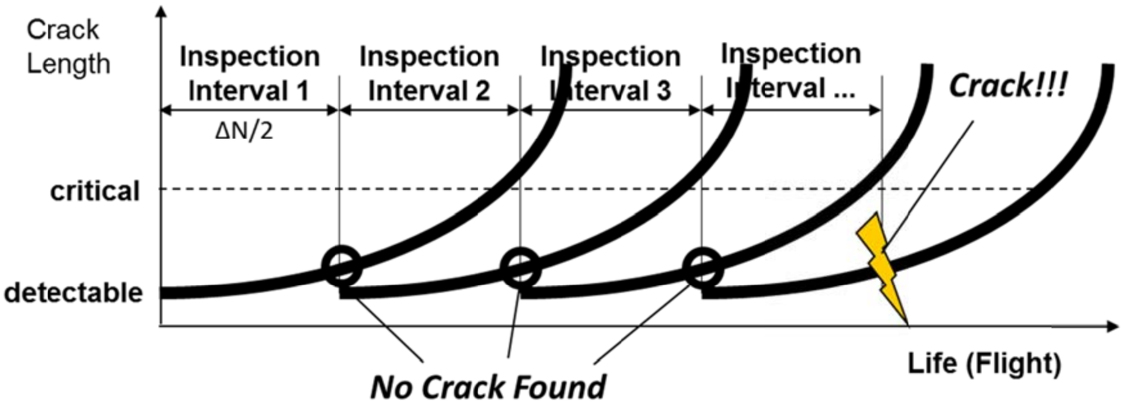


Fig. 2 The damage tolerance design principle

The reason aeronautics takes advantage of damage tolerant design is to design structures lighter weight what can be seen from the schematic fatigue life curve shown in Fig. 3. However, within civil engineering lightweight design may not be a design issue of paramount importance while the other parameter in the fatigue life curve being available to take advantage of is operational life, which is essential within the civil engineering environment. Hence applying damage tolerance to civil engineering structures can help the average operational life of the structures under consideration to be enhanced. The smaller (earlier) damage can be detected the larger the inspection interval can be defined. This is why inspection methods are considered which do detect damage even at a microscopic level, which occurs during a period when a structure is loaded under fatigue.

The fact that damage accumulation and hence damage progression is a non-linear process, specifically when loads applied to the structure are of an arbitrary nature too, and the maintenance processes can possibly be combined with fatigue life prognostic tools, the damage tolerance approach taken can have the advantage to predict the individual life of structures and with this to establish a maintenance scheduling plan in the end.

Assuming fatigue to be the critical damaging factor may lead to another issue with regard to the assessment, which is the availability of fatigue data. For many of the old infrastructure this data is either not or not sufficiently available and also the material is possibly difficult to be obtained. Furthermore the damage condition of the civil infrastructure to be assessed may not be sufficiently well known. Hence the most suitable way in assessing the structure's real damage condition would be to experimentally analyze material from the infrastructure to be considered. This however requires a method to be used that only requires a very limited amount of material to be taken from the infrastructure to be inspected.

A method that allows S-N curves and the respective material properties to be determined is PHYBAL (Starke 2007, Starke *et al.* 2010). PHYBAL is a short-time calculation of S–N and fatigue life curves of metallic materials. With PHYBAL the S-N and fatigue life curves for different metallic materials and material conditions can be determined on the basis of one load increase test and two constant amplitude tests only. A stepwise or continuous load increase test (LIT) is performed first to estimate the endurance limit and to select appropriate stress amplitudes for constant amplitude tests (CAT) with one single specimen. Fig. 4(a) shows the experimental approach as a principle. The LIT starts at a stress amplitude of $\sigma_{a,start}$ which is chosen below 25% of the materials' yield strength being increased stepwise by $\Delta\sigma_a$ after a defined number of cycles ΔN or continuously until the specimen finally fails. Along this test different other parameters being relevant to damage can be measured such as plastic strainε_{pl}, temperatureΔT, electrical resistance ΔR or even electromagnetic impedance Z (Fig. 4(b)). Within this procedure two relevant stress parameters are selected a) $\sigma_{a,LIT}$ being the stress level where one of the damage relevant parameters significantly changes from zero, which can be also used for the estimation of the endurance limit and b) $\sigma_{f,LIT}$ being the stress level at which the specimen fails. Two constant amplitude fatigue tests need to be further performed the one being slightly above $\sigma_{a,LIT}$ and the other slightly below $\sigma_{f,LIT}$ respectively.

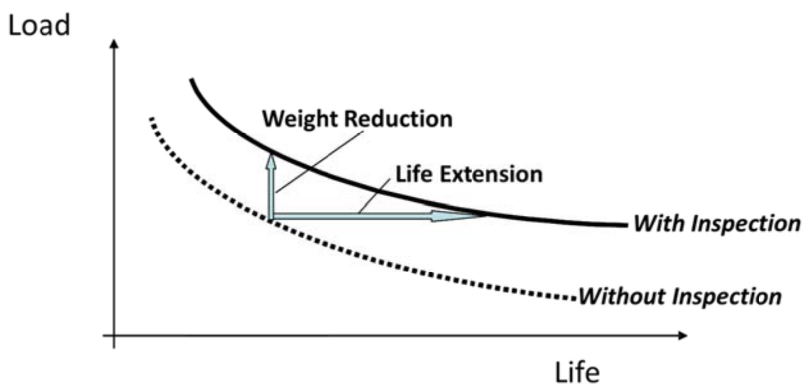


Fig. 3 Effect of damage tolerance principle on allowable fatigue life curve

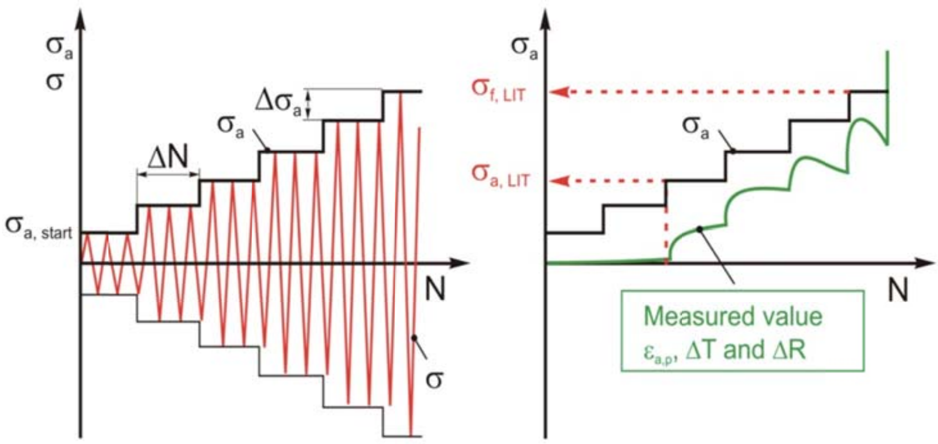


Fig. 4 A schematic view of stress amplitude σ_a (a) and measured values $\varepsilon_{a,p}$,ΔT and ΔR (b) in a stepwise load increase test

In the respective case for a quenched and tempered SAE 4140 steel shown in Fig. 5 where $\sigma_{a,LIT}$ has been 480 MPa and $\sigma_{f,LIT}$ has been 680 MPa respectively, the stress levels for these CAT have been chosen to be 500 MPa and 640 MPa respectively.

In Fig. 6 the stress amplitude is plotted versus the damage relevant parameters recorded in the LIT as well as the respective damage relevant value obtained at half of the fatigue life for the two CATs. To take the pre-damage of lower load levels of the LIT into account, the values of the two CATs are used as anchoring points for the transfer of the stress-damage parameter relation of the LIT to the one for constant amplitude loading by a linear interpolation function based on the stress amplitude ratios of CAT and LIT.

A power law proposed by Morrow (1964) is used to describe cyclic stress-strain (CSS) curves of the load increase test and the constant amplitude tests. This power law has been used in a generalized formulation with the cyclic hardening coefficient K'_M instead of K' and the cyclic hardening exponent n'_M instead of n' respectively, applying the different damage parameters M mentioned above such as plastic strain, temperature, electrical resistance or electromagnetic impedance, leading this power law to become

$$\sigma_\alpha = K' \cdot \left(\varepsilon_{a,p}\right)^{n'} \rightarrow \sigma_a = K'_M \cdot (M)^{n'_M} \tag{1}$$

A similar approach is made with regard to the S-N-curve where the Basquin Eq. (5) is applied. Here the fatigue strength coefficient σ'_f is replaced by the $\sigma'_{f,M}$ and the fatigue strength exponent b by b_M respectively, leading to

$$\sigma_a = \sigma'_f \cdot \left(2N_f\right)^b \rightarrow \sigma_a = \sigma'_{f,M} \cdot \left(2N_f\right)^{bM} \tag{2}$$

According to Morrow the fatigue strength exponent b_M can be calculated on the basis of the cyclic hardening exponent n'_M

$$b = \frac{-n}{5n'+1} \rightarrow b_M \frac{-n_M}{5n'_m+1} \tag{3}$$

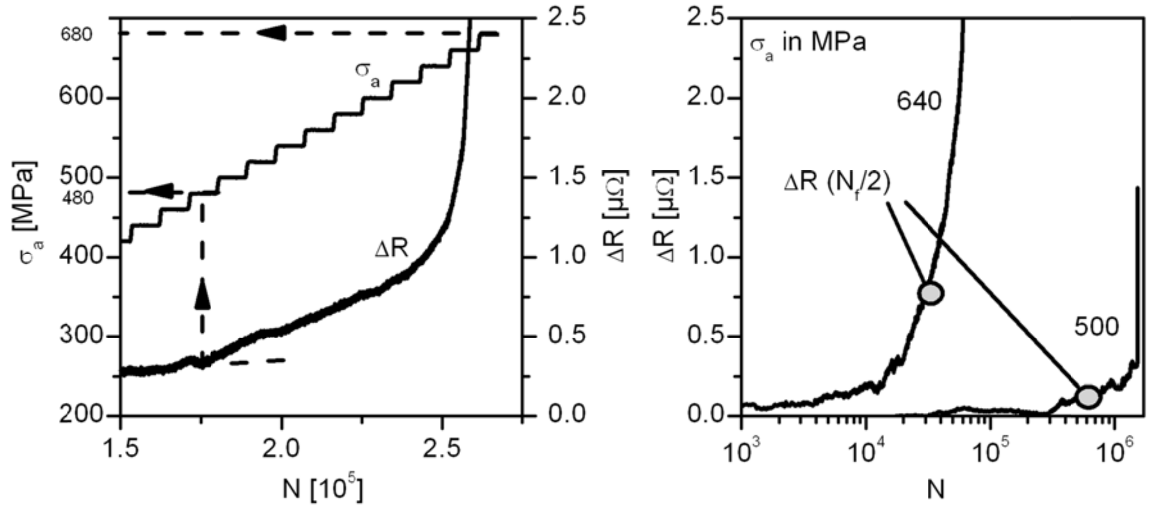
With the strain hardening exponent n'_M being known from the LIT the fatigue strength exponent b_M is determined and with the result of one of the CAT the fatigue strength coefficient $\sigma'_{f,M}$ can be determined from Eq. (2) too. This finally allows the S-N-curve to be described on the basis of b_M and $\sigma'_{f,M}$ only leading to

$$N_f = 0.5 \cdot \left(\frac{\sigma_a}{\sigma'_{f,M}}\right)^{1/b_M} \tag{4}$$

Fig. 6(a) shows results of proportionally downscaling CAT results from the LIT results and proving that a linear relationship can be drawn between the two CAT results obtained.

Fig. 6 shows on the right hand diagramme the S-N curve obtained with the PHYBAL approach and the good match with experimental data for the quenched and tempered SAE 4140. Compared to conventional fatigue testing and the way materials data have been presented in the past (Boller and Seeger 1987) PHYBAL is an approach that reduces the effort of generating materials data for cyclic loading by a factor of ten. In other words: This much more efficient provision of fatigue data is first of all a great help because it allows materials fatigue data to be provided even for an aged structure in terms of the material's residual fatigue strength. Provision of testing material may be possible in case a component of the aged structure considered may be replaced and the respective samples for materials data generation can be manufactured. However, if sample material has been taken from a component replaced on the respective structure it is still not known which degree of damage the material tested has. With much of the ageing infrastructure considered, data of the pristine material is not available and it is such that a relative approach has to be taken to obtain a more tangible value of the stage the structure under consideration is damaged.

The approach on how to obtain those more tangible values is through the design of the structure being considered. For this the geometry, type of materials and loads have to be known. It is specifically the latter which might have been initially assumed and which need to be monitored to obtain an adequate figure. This is reasonably possible today, specifically within the context of structural health monitoring (SHM), making use of the various types of sensors being available such as electrical or optical fiber strain sensors as well as vibration sensors of different kinds. Options of such a type of sensors including the monitoring concepts have been described in reference books such as (Boller *et al.* 2009). The outcome of such a loads recording approach may not represent the complete life of the structure considered, however, it does at least represent the shape of the loading spectrum and with this a major portion under which the structure has been operated. This now allows a fatigue life estimation of the structure to be made in combination possibly with a FE analysis and to determine at which locations damage has accumulated more when compared to others. This principally relative damage profile can then be finally referenced to the degree of damage of the component replaced where the samples for materials' data experimental validation had been taken from.



(a) (b)

Fig. 5 Stepwise load increase test (LIT) for quenched and tempered SAE 4140 with stress amplitude ε_a and change in electrical resistance ΔR related to fatigue cycles applied (a) and electrical resistance versus fatigue cycles applied at two stress levels of a constant amplitude test (b)

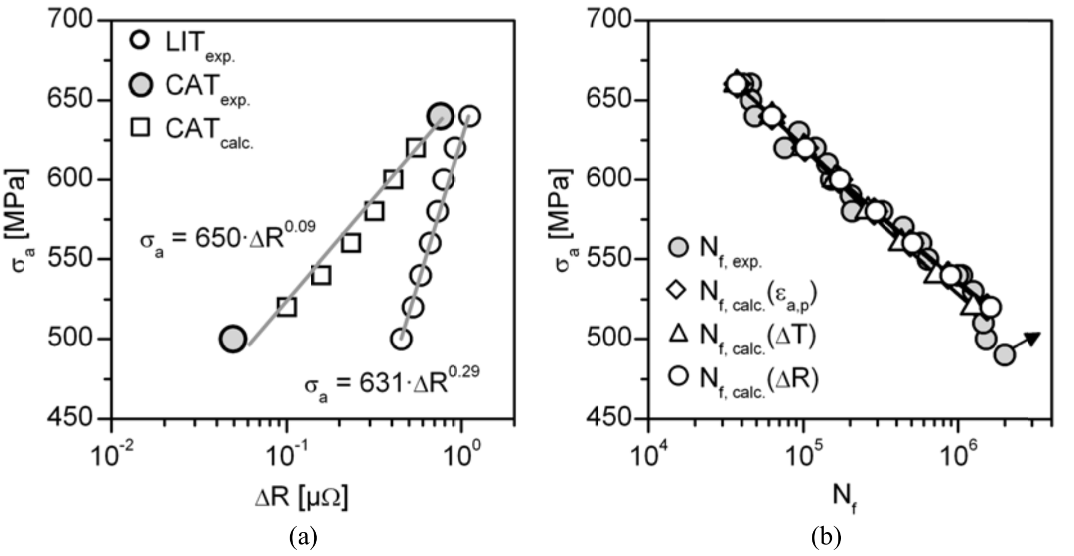


Fig. 6 Cyclic stress-resistance $\sigma_a - \Delta R$ curves for a load increase test (LIT_{exp}), ΔR values at $N = N_f/2$ for two constant amplitude tests (CAT_{exp}) and $\sigma_a - \Delta R$ curve calculated for constant amplitude loading (CAT_{calc}) (a) as well as comparison of experimental lifetimes ($N_{f,exp}$) and S-N curves calculated on the basis of $\varepsilon_{a,p}, \Delta T$ and ΔR for constant amplitude loading (b) for quenched and tempered SAE 4140

With this in mind and the PHYBAL approach described above it is now possible to locate the S-N curve within the range of different damage conditions including the pristine condition in a way it has been described by Haibach (2006) and possibly others and which is shown in Fig. 7 below.

The approach is based on an S-N curve to be described as a bi-linear function

$$N = N_E \cdot (S_a / S_E)^{-k} \qquad \textit{for } S_a \geq S_E$$
$$N = \infty \qquad \textit{for } S_a < S_E \tag{5}$$

where k, N, N_E, S_a and S_E represent the slope of the S-N curve, the number of cycles, the number of cycles at the endurance limit, the stress amplitude and the stress amplitude at the endurance limit respectively. This function can also be described for a material where the damage is $0 < D < 1$. In that case the S-N curve is shifted to the left when compared to the S-N curve for the pristine condition and the endurance limit is reduced along a locus shown in Fig. 7 which depends on a parameter q being a function of the way damage accumulates in the material considered. Knowing the relative degree of damage or better the damage distribution of the complete structure through a fatigue life calculation performed for the structure considered, now allows the degree of damage to be determined of the component that has served to determine the materials data in accordance to the PHYBAL approach. With this figure in mind and the material's data residual fatigue life determined from the PHYBAL approach the endurance limit and hence the degree of damage can be determined. If a possibly second material sample taken from another structural component having a different degree of damage condition and allowing for replacement can be made available, then a second S-N curve in accordance to the PHYBAL approach is generated which can finally allow the complete spectrum of residual life S-N curves for different damage conditions to be determined. This will then allow the structure considered to be fully assessed in terms of its residual operational life.

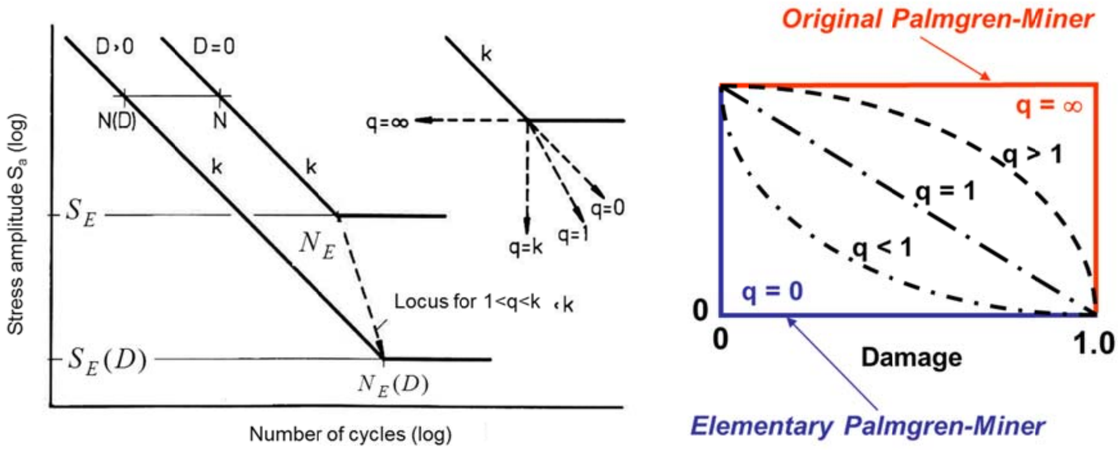


Fig. 7 Schematic of handling S-N curves for a material under different damage conditions

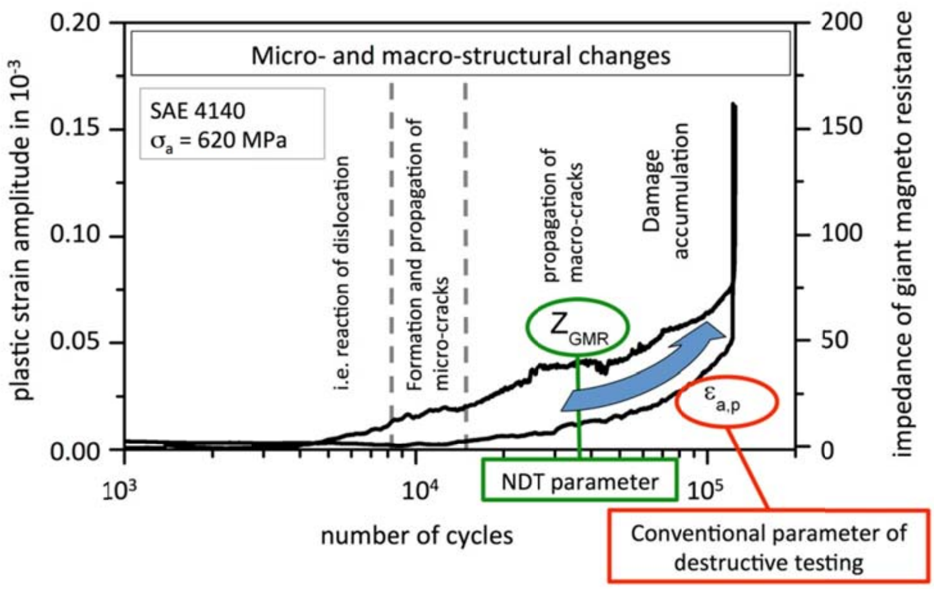


Fig. 8 Change of different physical parameters over fatigue life of a quenched and tempered SAE 4140 steel under constant amplitude loading with a stress amplitude of 620 MPa

The different damage parameters M considered such as plastic strain, temperature, electrical resistance or electromagnetic impedance are very much associated with physical parameters being used in nondestructive testing (NDT). Specifically electromagnetic techniques such as measuring eddy current impedance, permeability, higher harmonics or Barkhausen noise are techniques which have been used to characterize materials under different conditions including ageing at even sub-microscopic cracking conditions. An overview of the capabilities of those techniques with regard to describing mechanical conditions of materials has been provided in (Boller *et al*. 2011) and its capabilities in analyzing materials even at microscopic level has been described in (Sheikh Amiri *et al*. 2014) respectively. Fig. 8 shows the result obtained on a quenched and tempered SAE 4140 steel fatigue tested under constant amplitude loading with a stress amplitude of 620 MPa where the electromagnetic impedance has been measured using a giant magnetic resistor (GMR) (Starke *et al*. 2009). A sensitivity higher than measuring plastic strains has been determined which gives rise to the fact that damage and hence damage accumulation can be measured even below the stage where micro-cracking does emerge.

3. An Approach for lifecycle management of aged steel infrastructure

As to the methodology described above a lifecycle management concept for ageing steel infrastructure can now be established. It is based on the availability of the digital (FE) model of the structure considered including the load spectrum being applied to it. This model can be determined for even an old structure and can be continuously updated by monitoring strain sequences at well-selected locations. With this a fatigue life estimation becomes possible which allows damage accumulation to be determined at discrete locations of the structure considered where the locations become indicators for visible damage is to be expected first. Since crack initiation is a stochastic process a FE model may require an update with regard to the structural damage condition detected such that a more precise prediction can be achieved. This looks possible when NDT data such as with electromagnetic techniques can be sampled and correlated to the different damage conditions over a fatigue life. This may be performed along the LIT and CAT experiments in case the PHYBAL method is applied and will result in diagrams of the type shown in Fig. 6. This will describe the non-linearity of damage accumulation and may serve as the calibration source once it has been normalized such that the non-linearity in damage accumulation can be literally applied all along the S-N curve. It will significantly help to circumvent the errors made when applying linearized damage accumulation rules such as proposed by Palmgren and Miner. Performing electromagnetic sampling at various locations of interest along the structure considered on the other hand will allow a full profile of the electromagnetic parameters over the structure to be generated. This profile of electromagnetic parameters can be converted to a stress distribution profile based on the information provided in Fig. 6. Merging this with the damage parameter progression curve obtained for a CAT performed at a defined stress amplitude such as shown in Fig. 8 will principally allow a reference point with regard to the degree of damage and hence the number of cycles to be found, which will then allow the damage profile of the structure to be determined in even absolute terms. This profile can be matched and further updated with the fatigue life predictions made and will principally allow for a continuous model update gradually refining any damage assessment models such that the structure considered can be managed in terms of maintenance, repair and overhaul in the longer term. With sensing devices such as monitoring loads or damage being even placed stationary at damage critical locations will allow a way of structural health monitoring to be performed on a wireless basis making management of a large number of steel infrastructure possible from a central location only.

4. Concrete infrastructure assessment

Concrete is a material much more difficult to understand with regard to its damaging behavior when compared to metals. It is a composite material at macro-scale of a mainly brittle nature, which can be pre-stressed and may possess cracks already at its onset. It is not exposed to mechanical loads only but also to environmental loads where moisture, corrosion and resulting carbonation can play a significant role. Concrete structures as they are designed today as well as in the past are said to be principally damage free. This is however far from reality as can be seen with an increasing number of concrete structures worldwide now deteriorating.

The approach on how to assess a concrete structure with respect to its life cycle management is principally similar to the one applied for steel. Damage could be tolerated provided the criticality of the damage is known and the way the damage progresses from a detectable to a critical stage. The way concrete structures are assessed today is mainly by visual inspection only. The structures are then categorized such as in accordance to a traffic light system, which must be considered as a rather subjective approach. Application of NDT in civil engineering can still be considered to be in its infancy. First publications in this field appeared in the mid 1980ies and there is still not much NDT technology being already available which possesses the maturity to be standardized. Overviews with regard to some latest developments of NDT in civil engineering can be found in (Kurz *et al*. 2011, Dobmann *et al*. 2010) as well as in the proceedings of some recent conferences (Wiggenhauser *et al*.).

If damage tolerance was to be applied to concrete structures then much inspection would have to be required since the period from when first cracking may be observed on a concrete structure up to a condition where concrete coverage falls off due to corrosion at and carbonation along the metallic rebars may be short or at least fairly impossible to predict. Frequent inspection calls for automation of the inspection process and this inspection can become risky, specifically when a structure becomes large such as in the case of a bridge. Automation of the process using a robot (or multiple robots) equipped with sensors such as digital cameras is therefore an option interesting to be explored since it can be used to replace the human inspector. The approach having been taken for inspection is based on a micro aerial vehicle (MAV), which is equipped with a digital camera underneath such as shown in the case of an octocopter in Fig. 9. The MAV is flown remotely and scans the building to be monitored. The camera is set in a continuous trigger mode 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 can operate GPS based, the entire flight process is manually controlled. This is due to the lack of GPS signal when the vehicle flies close to the structure to be monitored. The autopilot together with some additional features such as a vector thrust propulsion system only provides auto-stabilization and altitude control. Flight stability of the robotic vehicle is important since it is directly correlated to the quality of the images taken.

To successfully run the photographic monitoring initially, a flight route well planned is most essential. For a camera with an image ratio of say 4:3, a horizontal flight route scanning will produce a series of pictures with lowest achievable distortion, which is the reason why a horizontal scanning is usually preferred. During the monitoring process a volume of several GB of images is easily accumulated. From those images only a fraction of the best can be taken for being stitched together. To enhance that fraction of useful images different measures have been taken in terms of stabilizing the MAV's attitude control through a vector thrust system and optimizing the waypoint control through a fuzzy logic control algorithm built into the camera system (Kuo *et al*. 2014). To speed up the image stitching process automated image stitching tools have been used as well. However, manual corrections are still required when structures are photographically 'assembled' of the dimensions shown in Fig. 10. The resolutions to be obtained in the end are those shown in Fig. 11 where a cracking pattern is observed on the left. Such cracking patterns are typical in concrete resulting from carbonation and corrosion along rebars and are a precursor that concrete parts are due to come off. Tools for clearly identifying such cracking patterns along an automated process are therefore essential for which a resulting picture can be seen in the middle of Fig. 11. Once time passes by, concrete parts will come off as is shown for the same location on the right hand side of Fig. 11. This also shows one of the advantages of automated imaging using a MAV.

Fig. 9 Octocopter MAV system with digital camera

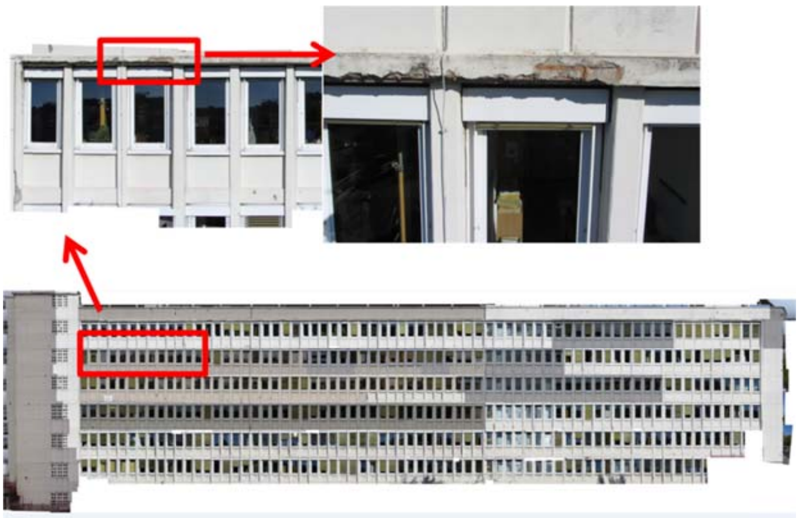


Fig. 10 Stitched images of a major building (bottom image) with resolutions to be zoomed in (top images). Note that different colors of images are due to images taken at different weather conditions

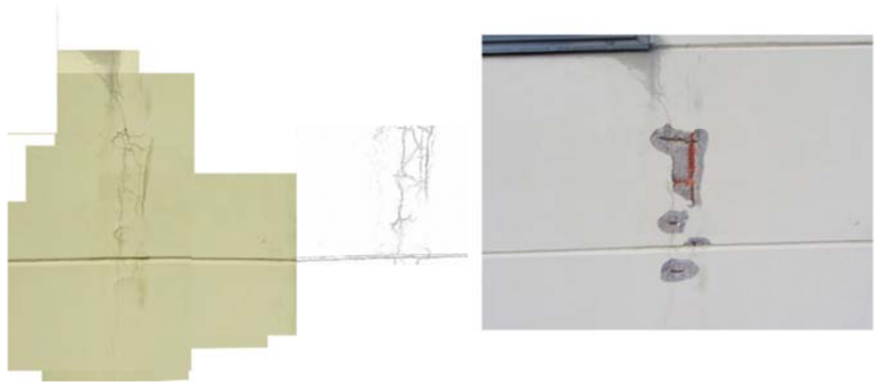


Fig. 11 Damage in a concrete wall (left), resulting crack pattern (middle) and damage 11 months later (right)

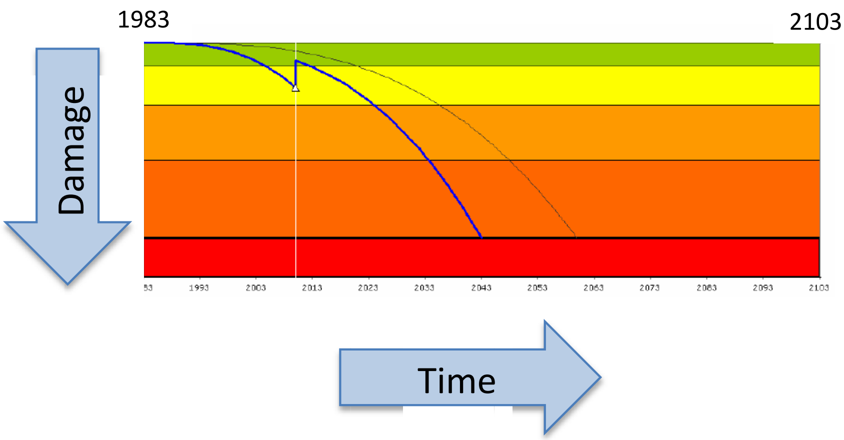


Fig. 12 Theoretical global life cycle curve for a bridge and resulting impact due to enhanced maintenance

Once an infrastructure such as a building has been fully recorded and possibly modeled in 3D, only the critical locations have to be recorded in later stages, making this method of infrastructure monitoring highly efficient when compared to the conventional methods where men have to climb along critical maneuvers to access the locations of interest. Taking images of those critical locations at close intervals will allow a sequence of the damage incubation and progression process to be constructed that may allow the still mainly unknown damage mechanisms in concrete to be assessed and better understood. With the ability to further allocate each pixel geometrically a means will be provided to generate a full map of damages present at least in 2D. With the inclusion of further NDT techniques such as radar or thermography further means will be provided that will allow the structure to be monitored sub surface. By merging those data with the visually obtained data through a data fusion process one will gradually obtain a 3D image of the damage that will further allow the damage mechanisms observed to be better understood.

4. Conclusions

Inspection of civil infrastructure such as bridges has been increasingly improved over the past decades. With FE modelling emerging as an established technique, stress, strain and temperature distributions in structures have become viably determinable. Similar observations regarding simulation can be made with regard to the dynamic behavior of structures. The consequences of loads applied to structures can therefore be simulated and with the emergence of a variety of sensors those loads can be monitored too. Hence a fairly realistic loading behavior can be simulated in structures which again can be correlated to the resulting damaging behavior of the structural material considered. Description of this damaging behavior is qualitatively different with respect to the type of material and the type of damage considered. With metals and fatigue the degree of damage modelling is comparatively advanced while with corrosion it is already less and becomes close to zero when moving to other types of materials such as concrete, wood or polymer based composites. This leaves visual observation and assessment as the only option and denominator in getting the condition related information retrieved and to be combined with the structural design methods applied.

Keeping this general state-of-the-art in structural assessment in mind life cycle assessments of metallic structures can be well performed and can even be expanded from a traditional safe life to a damage tolerant approach. Combined with destructive and nondestructive assessment techniques a structural material's damage condition can be characterized and merged with prognostic tools such as used for fatigue life evaluation. In that regard the PHYBAL approach provides a significant progress since it allows much more fatigue related material information to be retrieved from a material's fatigue test than this has been possible in the past. This opens a new quality and potential in structural assessment specifically also with the increasing amount of ageing infrastructure. Based on monitoring the operational load spectrum with specific sensors at dedicated locations the residual life of principally each structure can be determined in the case of metals allowing individual maintenance programs to be established in accordance to operational needs. With the additional introduction of a damage tolerance principle this can further help to postpone maintenance actions and alleviate pressure that might have been imposed when conventional safe life time-based approaches would have had to be performed.

When considering the case of concrete structures, visual inspection is the only approach accepted for structural assessment currently. Even if other more efficient non-destructive testing techniques might be accepted in the future, visual inspection will still build the basis as it has been with metallic structures too. Establishing a monitoring approach therefore on the basis of visual inspection is logic for whatever material a structure might be made of, specifically when the image is on a digital and hence pixel basis. This pixel-based digitized information builds a basis into which additional information can be hung and that can be fed back as an image just in the way information on a structure's condition should be communicated even to people not being experts with respect to damage analysis and SHM.

The approach being proposed here provides a variety of elements that as a combination meets the requirements and definitions set for SHM to be performed (Boller 2009) and it can be seen as an amendment to what has already been compiled in (Boller 2009) and possibly other pieces of reference. With such a diagnostic and prognostic approach a means is therefore provided that allows structures to be better assessed in terms of their degree of damage as well as their residual operational life. Generating such a type of such damage related information is important in at least two regards. First of all it allows to better differentiate the degrees of severity of the different damaging condition of a structure which then allows respective maintenance actions to be planned in much more detail and more efficiently than this is done conventionally today. This is important from the point of view that maintenance actions do have to be optimized from a cost and organizational point of view and to which the approaches proposed here do contribute. Furthermore the digitally based approach resulting from the pixel based visual inspection provides an excellent data base onto which any further structural information retrieved from other NDT techniques can be added and built upon. This will allow true log files of structures to be established in the future and allow a structure's integrity history to be retrieved in much more detail than this has been done before.

The damage tolerance principle as a tool of life cycle management of civil infrastructure is therefore principally applicable to any type of structural material. However where the material's damaging behavior is better known such as with metals more of the prognostic capabilities can be taken to substitute the inspection effort while with other materials such as concrete a larger inspection effort is required until prognostic tools will become available one day. This larger inspection effort can currently be compensated through robotic inspection. That the damage tolerance principle is becoming viable in civil engineering has been proven with some life cycle analysis and management concept proposed in (Wenzel *et al*. 2013, Veit-Egerer *et al*. 2013) where deterioration of a civil infrastructure is determined as a scatter band as shown as an example in the diagram of Fig. 12 considering the variety of possible uncertainties involved. This diagram principally does not display anything else than an inversion of a crack propagation curve s shown in Fig. 1 before. However what Fig. 12 additionally shows is the criticality of the damage in terms of a traffic light system and what implications investments in maintenance would have, shown by the kinks in the lower bound degradation curve. With such a procedure the drawbacks of negligence in maintenance can be clearly visualized even to the non-engineering community and a first steps towards a more efficient life cycle assessment and resulting management of civil engineering structures can be made.

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