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INTEGRATED LIFE CYCLE MANAGEMENT OF AGEING STEEL INFRASTRUCTURE BASED ON SMART TECHNOLOGIES

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Summary: *The increasing age of infrastructure such as bridges or tall buildings requires a significant effort to be performed with respect to inspection such that damage being considered critical can be recognized early in advance and a respective infrastructure management can be performed. Such an inspection today may require a remarkable effort such as specific, very costly and unique inspection vehicles to be used which will lift inspectors for mainly visual inspection to the infrastructure's locations being damage critical and hence of interest. This paper describes on how such an infrastructure can be inspected in a much more efficient way using micro aerial vehicles (MAV) together with some destructive and non-destructive techniques to be added for a time, quality and cost efficient structural assessment. The MAV is first equipped with a high resolution camera that monitors the infrastructure visually, allows for damage critical locations to be observed and a 3D image of the infrastructure to be obtained, avoiding inspectors to be moved around the infrastructure under partially very critical operational conditions. From the 3D image obtained a digital model of the infrastructure can then be constructed, that allows a simulation of the infrastructure's loading and a resulting damage accumulation to be performed at least from a numerical point of view. The damage accumulation simulation obtained as a damage distribution map is then validated by some electromagnetics based non-destructive testing techniques. Data obtained with those techniques can then be fed back into the simulation system allowing a full map of the infrastructure's damage condition to be retrieved and the most damage critical locations of the infrastructure to be identified, although no damage may be observed visually. The approach made will be explained along an old steel bridge having been inspected and how this approach can be used in enhancing an old infrastructure's life cycle management process in terms of structural health monitoring.*

1 MOTIVATION

In many places around the globe there is an increasing number of infrastructure ageing. Although ageing much of this infrastructure is an asset for the national economy and thus has to be preserved by all means. Examples include bridges or towers made of steel where the design life may have been targeted at 50 or even 100 years of safe life operation. In many of the cases this lifetime has now been exceeded by 50% or even more. In many of the traditionally developed countries such bridge infrastructure may be in average nearly 100 years old with the upper limit approaching even 200 years already. This increase in age is possible due to uncertainties/scatter in loading conditions, material properties and specifically measures of maintenance taken. Maintenance is associated with inspection and the older an infrastructure becomes the more maintenance and hence inspection it requires, specifically the longer one waits with maintenance measures to be done. An economically efficient approach in that regard is predictive maintenance. Predictive maintenance consists of sensing an infrastructure's performance in terms of loads applied and material conditions achieved and merging this with materials properties describing a material's ageing process allowing a prognosis of the infrastructure's performance to be made. To be independent of any loading and material property uncertainties, an inspection has to be performed at defined intervals where the intervals are proportional to the number of loading cycles up to which damage is due to grow from a detectable to a critical size. This is what is called the *damage tolerance approach* and what is schematically shown in Fig. 1 below.

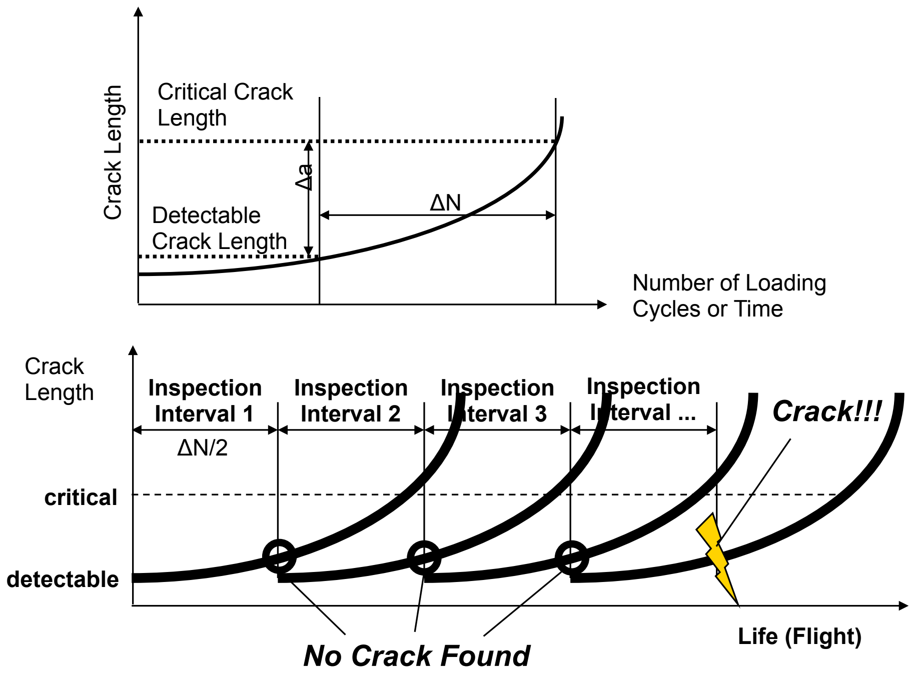


Figure 1: The principle of damage tolerance approach

Although not considered initially in civil infrastructure design damage tolerance is now becoming increasingly important in terms of infrastructure management and is gradually introduced ex post. A good example for this can be found in [1,2], where degradation of an infrastructure is predicted based on a variety of inspection parameters retrieved. Consequently since damage progresses in a non-linear exponential way the maintenance effort required progresses in a similar exponential non-linear way too. Hence the earlier maintenance can be done the lower the effort/investment required will be to a certain degree where the economic optimum has to be found respectively. This approach is associated with some regular inspection where the intervals of inspection have to be supported by some prognostic tools. How this can be done along a life cycle management process for a steel structure based on damage tolerance using smart technologies is described in the following.

2 THE LIFE CYCLE MANAGEMENT PROCESS

To assess a structure the loading conditions as well as the geometry and the material used for this structure have to be known. This information may be retrieved from design documents. However, in many cases this information may not be available anymore with an old structure or conditions have changed such that a reassessment of the structure may have to be performed. This requires the current operational loads to be determined as well as the shape of the structure considered and last but not least the material used in terms of its type as well as its properties. With this the status quo of the structure is determined and it is from this point where prognostics can start. Prognostics require additional information of a material's performance such as fatigue to be available. This information is often difficult, troublesome and costly to be obtained, specifically with steel types from the past being not manufactured anymore. Means on how to get this materials' data obtained in a very efficient and quick way has been described for a method called PhyBaL where further details have been described in [3-5]. With just three fatigue tests performed on an un-notched specimen a complete fatigue life curve of a material can be determined and this data does then allow residual fatigue lives of the respective structures to be determined on a prognostic basis. This fairly limited amount of material may be obtained from the ageing infrastructure under consideration by replacing an existing part of this infrastructure by a new one and using the retrieved part for manufacturing the un-notched specimens. An open question still remains as to which degree the material retrieved from the infrastructure and used for characterisation has already been damaged. This question may only be answered once the material has been characterised. Principally this degree of damage varies depending on the loading conditions applied as well as the stress concentrations resulting from notches within the infrastructure's geometry and where the sampling material has been principally retrieved from. With the PhyBaL approach principally a relationship between a fatigue damage characteristic parameter and fatigue life is established, where plastic strain has been traditionally considered to be a fatigue representative one. Recently electromagnetic impedance has been found to be possibly even a more sensitive parameter with respect to fatigue damage, since it already reacts to damage at microscopic level, where plastic strain still possibly fails to react. If the development of fatigue damage can be correlated to electromagnetic impedance, then principally the damage condition of each single location on a ferromagnetic structure can be determined. This relationship has been proven in a variety of different cases for which an example is shown in Fig. 2 below. This relationship can also be proven for any material for the three fatigue experiments required to be performed with the PhyBaL approach which generates a relationship between electromechanical impedance and fatigue life and hence an evolution of electromechanical impedance and hence damage over fatigue life in general. If this relationship can be proven in generalised terms then a method is found that allows damage to be determined at virtually any location of a structure by virtually measuring a non-destructive testing (NDT) based parameter such as electromagnetic impedance. Even in the case the material retrieved from the infrastructure is aged and hence damaged to a certain degree already it is still thinkable to determine the the original fatigue life data of the material considered through specific means of extrapolation.

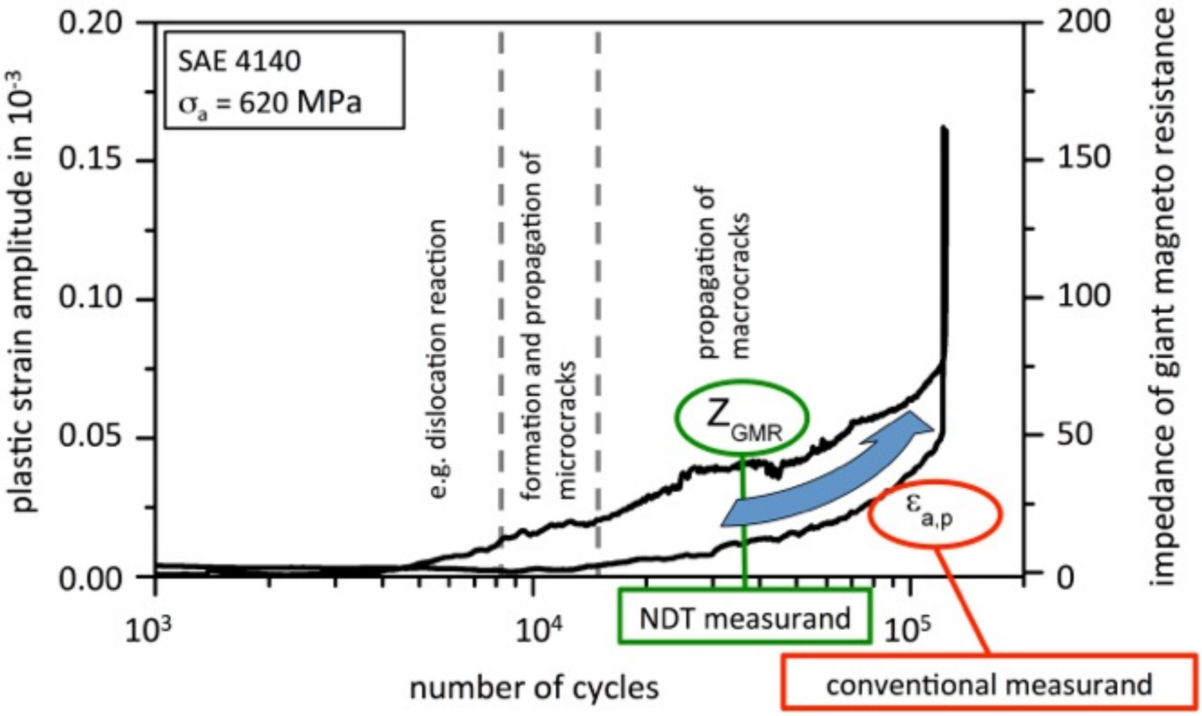


Figure 2: Development of electromagnetic impedance and plastic strain amplitude over a constant amplitude fatigue test

A validation fatigue damaged structures may therefore be done using electromagnetic impedance as the on the NDT parameter. With this instrument now in place a life cycle management process can be initiated, where a structure's initial condition can be assessed and its degradation can be predicted such that inspection intervals can be defined. The elements of this do include:

- Infrastructure initial condition assessment in terms of a structure's:
  - Load spectrum applied
  - Shape (i.e. structural geometry in terms of notches and stress concentrations in general)
  - Structural materials used
  - Structural stress and strain analysis performed
- Periodic inspection
  - Damage prognostics
  - NDT based inspection.

These elements are detailed in the following sections in terms of potential smart technologies to be used.

3 INFRASTRUCTURE INITIAL ASSESSMENT

Loads on infrastructure normally vary. As such the loads applied have to be defined as a load spectrum. This load spectrum may be either given as a design spectrum or may have to be determined through measurement. The latter requires a load distribution model of the structure considered i.e. in the form of a FE model such that the location on where to monitor a load sequence best can be clearly identified. Sensing devices traditionally used are electrical strain gauges, which require a lot of wiring and may be sensitive to a variety of environmental influences making them difficult to operate. A much more elegant way is the use of optical fibre sensors and here specifically Bragg grating sensors where a lot of the background and potential applications specifically for the civil engineering environment has been provided in [6] and will not be described in further detail here. The load sequences being monitored over a representative period of time can be assessed in terms of load cycle counting methods such as the Rainflow counting method reported in textbooks such as in [7].

Another important aspect is to determine the appropriate shape and hence geometry of the infrastructure to be assessed. With smaller components this may be done with a hand held monitoring device, however with civil infrastructure such a monitoring device has to be moved by other means. A means on how to do this attractively is by use of micro aerial vehicles (MAV), which are little unmanned aircraft with up to a take-off weight of 5 kg and a span of around a metre. Those vehicles are equipped with sensing systems of different kinds, where the first approach is to simply equip the MAV with a digital camera system of which an example is shown in Fig. 3 below. The type of MAV used for infrastructure inspection is a rotary wing type MAV due to its ability to hover and hence to perform detailed monitoring of an infrastructure as good as possible. Typical solutions for this are quattro-, hexa- and octo-copters respectively.

Figure 3: Example of an octo-copter equipped with a digital camera system

The challenges and smart technology options being required for those vehicles have been well described in [8]. They include a flight route scanning strategy, image stitching techniques for generating even 3D images of the infrastructure monitored and different features for flight stabilisation such as vector thrust steering or fuzzy logic control of flight path planning. With these an improvement in 3D construction of the infrastructure has been achieved as has been shown with some 3D reconstructions made such as shown as an example Fig. 4.

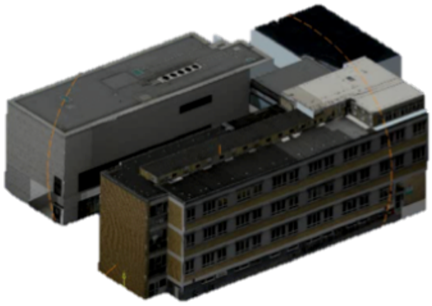


Figure 4: 3D image of a building complex obtained from stitching a large number of photographic images taken by a MAV

These options allow structural geometries of an infrastructure to be generated which is important when drawings are missing and a model of the structure has to be regenerated, possibly even in 3D to be further converted into a CAD and FE model respectively. However, this is currently still not at the level of being fully developed since the true distance information for a precise 3D reconstruction is still missing. Means of getting this achieved is by replacing the camera with a laser sensor, where the replacement option is required due to payload and endurance restrictions of the MAV.

The requirement of using a high-resolution camera is also associated with the fact that not just the geometry of the infrastructure is due to be recorded but rather also the structural material's condition in terms of damages such as cracks, corrosion and others. Those damages may be in the millimetre range only and will therefore require a fairly stable flight and a high-resolution camera or sensing system in general.

As regards the material properties of a possibly ageing material those have to be principally determined in conventional terms in the case of steel. This requires some material to be replaced on the infrastructure considered where the material removed is the one being used for experimental characterisation. Luckily with the PhyBaL method [3-5] only a very limited amount of material is required. However, since the material being tested is taken from a component having possibly been loaded and hence damaged in a non-homogeneous way it is essential, that the load distribution in this component is known from a stress analysis performed before. The fatigue tests performed with the PhyBaL method will generate data such as electromagnetic impedance being a parameter well established in NDT. This is important since the NDT parameter will be further used to assess the condition of the steel infrastructure during its residual life in accordance to the life cycle management approach described further above.

In a variety of different studies electromagnetism with various of its facets has been proven as a powerful tool for fatigue damage assessment where only a fraction of those are referenced here [3-5]. An approach with a resulting hardware testing device to be used is the

3MA approach, which has resulted in an experimental equipment such as 3MA [9] or MikroMach [10]. MikroMach being used here is a handheld device of which the principle is shown in Fig. 5. It consists of a yoke, an actuation coil, a Hall sensor, a power generator and the respective electronics and is linked to a laptop from which the device is controlled and data are processed and visualised. Electromagnetic methods considered include multi-frequency eddy current impedance, incremental permeability, Barkhausen noise and higher harmonics analysis all being described in further detail in [9]. Those electromagnetic techniques will allow the structural materials damage condition to be assessed already at a sub-microscopic stage of cracking.

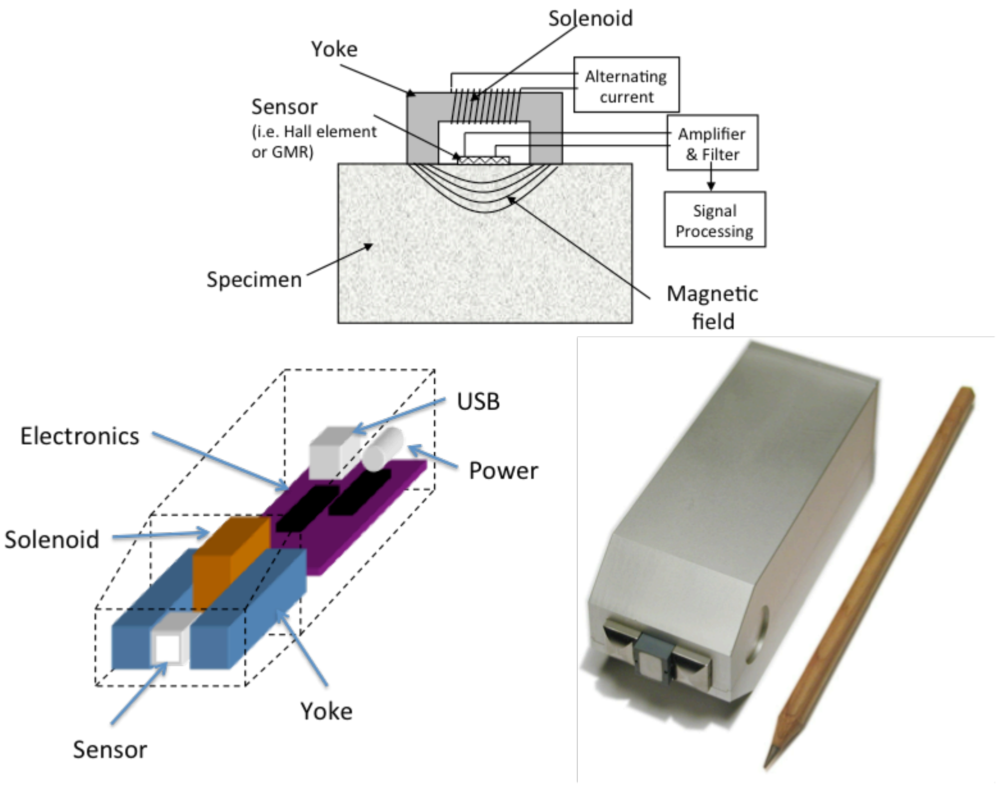


Figure 5: MikroMach system for electromagnetic characterisation and principle

The electromagnetic information is to be taken as a basis for residual life assessment of the infrastructure considered. This can now be done in a way that electromagnetic data are taken from selected locations on the infrastructure to be monitored, those data are related to the materials characterisation data (i.e. impedance vs. life) determined from the materials characterisation tests under the PhyBaL approach described above which does finally result in a damage distribution map of the infrastructure considered in the end.

4 PERIODIC INSPECTION

Once the initial condition of the infrastructure to be inspected has been assessed and documented a follow-on (residual) life cycle management process can be formulated. From the loads being continuously monitored at well-selected locations on the infrastructure and with the existence of a digital (FE) model of the infrastructure a stress and strain distribution in terms of a load transfer function can be calculated. This allows for example a continuous numeric fatigue life estimation to be performed in the classical fatigue life evaluation approach using materials data such as an S-N-curve and the load sequence respectively and predicting the fatigue life at virtually any location of the infrastructure. This prediction will at least determine where damage is due to occur first and where inspection will have to happen first as well. Knowing that the numeric fatigue life evaluation approach mentioned above is not very precise due to various assumptions made such as the linearisation of damage accumulation and also others a continuous or at least regular inspection with the electromagnetic testing device at damage representative locations on the infrastructure is useful to continuously correct the error in the numeric damage accumulation estimation made. With this a fairly precise prediction of crack initiation at the infrastructure's damage critical locations should be feasible, that could be inspected in situ visually with the MAV-based inspection system mentioned before provided the crack considered can be accessed visually with the MAV system and may be difficult to be accessed by other means.

5 TEST CASES

Adaptronica has been analysing a steel railway bridge in Poland along some different projects in the past. The bridge as shown in Fig. 6 where the age of the bridge is not fully clear but has to be estimated to be 50 years old or more.

Figure 6: Railway steel bridge analysed for inspection purposes

Images of the bridge have been taken at high resolution with the MAV (Fig. 7) and it turns out when magnifying those further that one is well able to obtain a resolution similar to an inspector's view. This is at least possible with respect to the locations being accessible to the MAV.

In another trial the lower steel deck of a motorway bridge in Germany has been analysed with respect to cracks generated along the welds of some fillets. Fig. 8 shows a picture taken from a basket lift just in front of the fillet joint (left) and a picture taken of the same location by the MAV. Quality of the images is fairly equal however the effort in obtaining the images differs roughly by a factor of 10.

Figure 7: Detailed view of structural joint

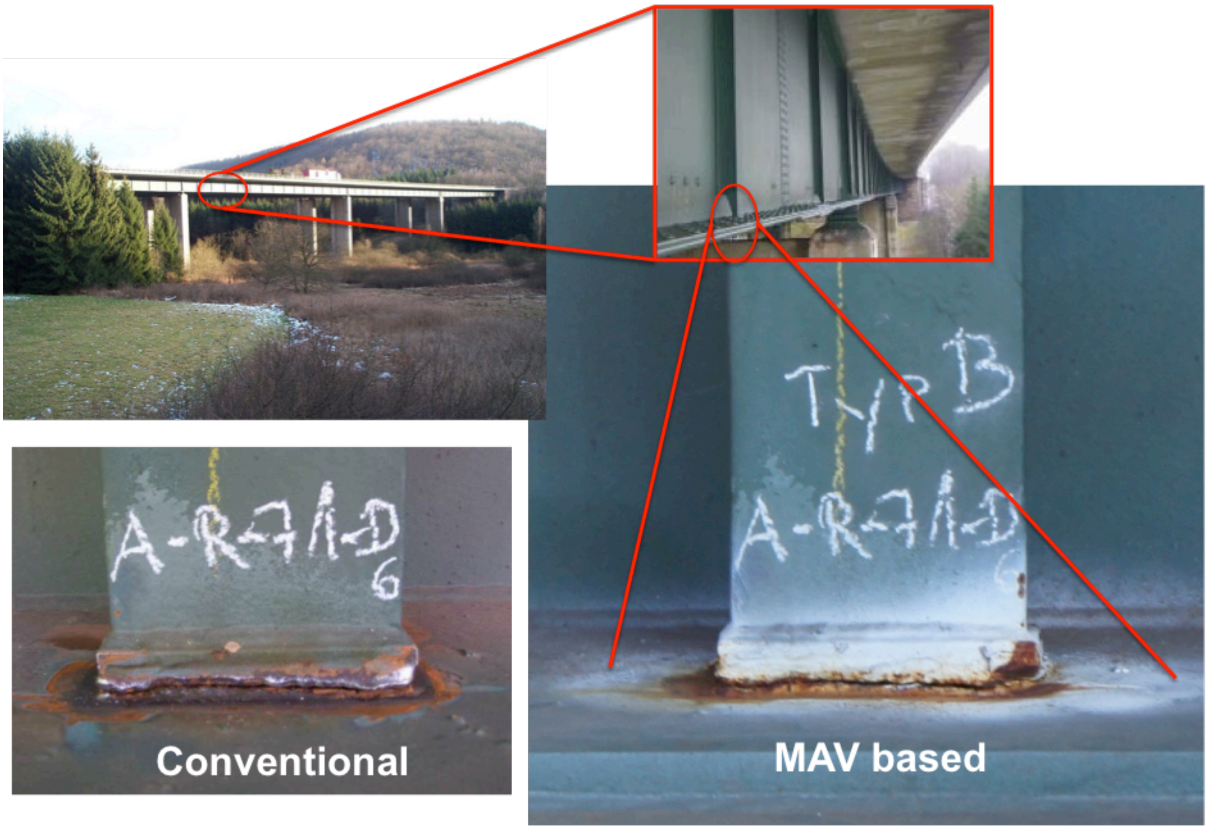


Figure 8: Comparison of detailed views of a damage using a MAV based imaging system (photos partially from Landesbetrieb für Straßenwesen Saarland)

A next step in MAV-based infrastructure monitoring is to generate a 3D image from the infrastructure to be monitored. This has become well feasible in the case of buildings where the surfaces are fairly flat and less profiled when compared to the much more complex steel structures referenced above. Fig. 9 shows images stitched from two types of buildings, a historic tower (left) and a multi storey brick wall (right). Magnifying the images taken from the brick wall shows that cracks being observable with the naked eye when being close to the brick wall only, can be determined through MAV-based imaging as well.

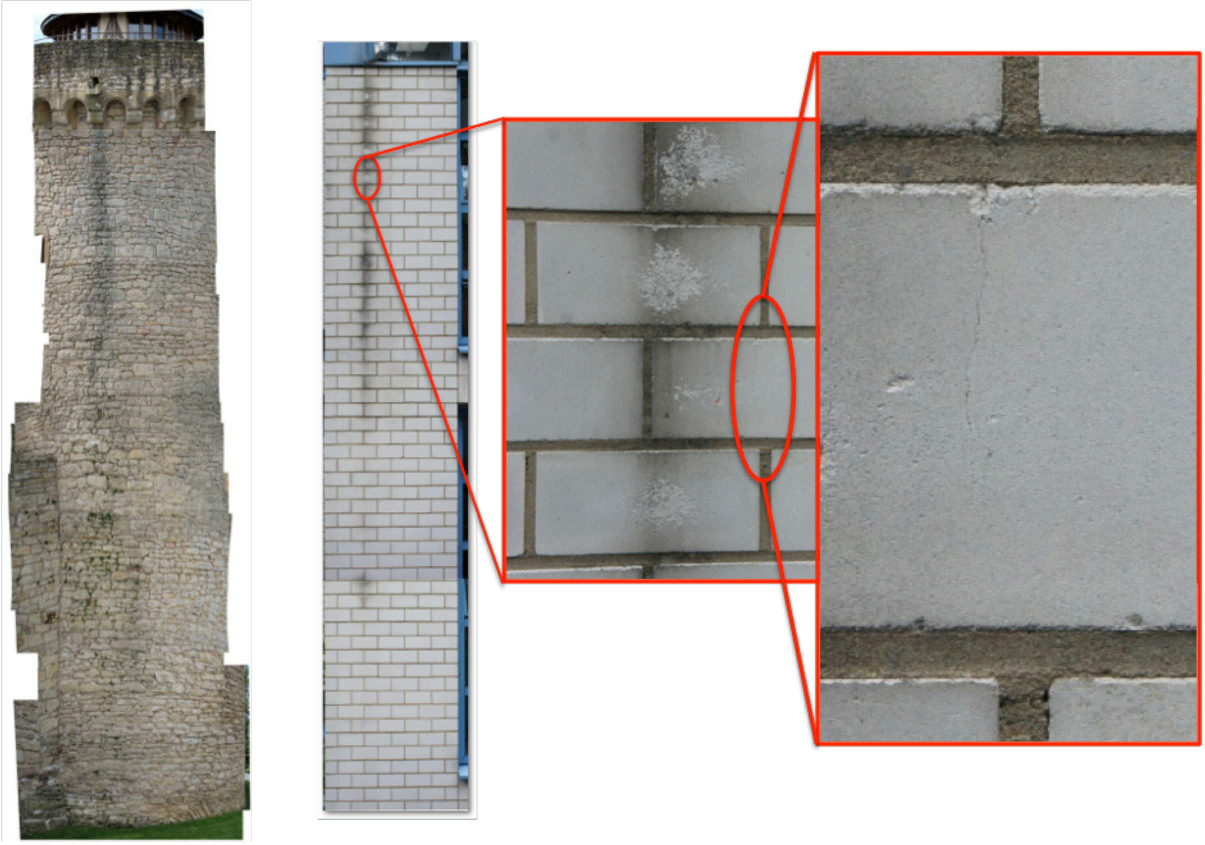


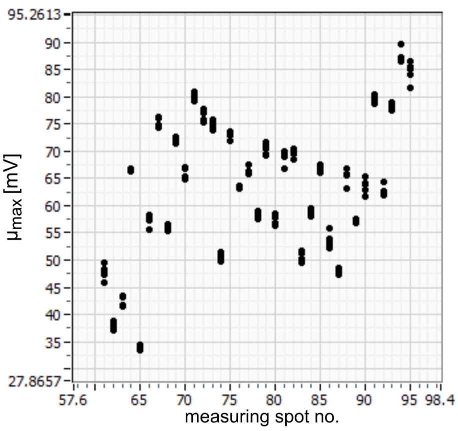
Figure 9: Different results and resolution from stitched images: historic tower (left) and multi storey brick walled building (right)

A next step along the assessment of the steel structures referenced above is to generate a 3D model as well. This is a rather more complex task since it requires a more detailed distance measurement, which is only achieved by either a laser scanning or some other advanced optical monitoring devices, which are currently in the process to be explored.

Once the 3D modelling of the structure considered has been completed in the form of a CAD model this model can then be transferred in a FE model that will allow stresses and strains resulting from the loads being applied to be determined. This will then also allow fatigue life calculations to be performed, which will lead to numerically determine the distribution of damage along the bridge structure. With this an experimental validation can now be performed using the micromagnetic techniques mentioned above. In the case of the bridge shown in Fig. 6 a first set of micromagnetic data has been taken using the MikroMach system shown on Fig. 5 above. Data were retrieved from one of the two beams that support the track where two of the sampling locations are marked on the photo shown in Fig. 10. The reason why this component has been chosen first is because of ease of access and the fact, that this component is fairly in direct contact with the traffic loads being applied.

Measurements were carried out as a length scan over half the length of the bridge, starting from one abutment up to the middle of the bridge. This corresponds to a length of 20 meters. The total number of measuring positions was 35. Each point was measured twice: once with a magnetization in the direction of the track and once perpendicular to it. In Fig. 11 the results obtained from the incremental permeability measurements are shown as a function of the different measurement positions. A large scatter can be observed from this first dataset taken, however with some trends to be observed. At about 8 meters from the abutment a heavy inspection trolley of around 1.3 metric tons was hung under the bridge. This position is well visible in the diagram at around measurement position no. 70. This effect is more marked when magnetization is parallel to the track than when it is perpendicular to it because in the latter direction no mechanical loads are expected from passing trains or net weight.

Figure 10: Data sampling points on bridge structure



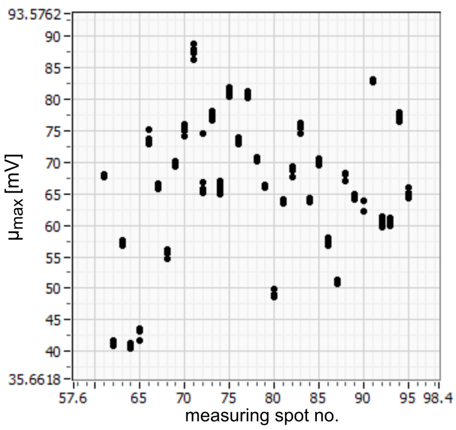


Figure 11: Incremental permeability measured along the track beam. Measurement spot no. 61 corresponds to the abutment and no. 95 to the middle of the bridge respectively. Magnetization horizontal and parallel to the track (diagramme left); Magnetisation horizontal and perpendicular to the track (diagramme right).

From the data shown specifically on the left hand diagramme in Fig. 11 it can be seen that there are two turning points along the data sequence shown being around measurement points no. 68 and 76 respectively. The locations of those two points are also the points where each of the triangular truss elements of the framework are linked together and where loads are hence introduced. Since each of the horizontal lower truss elements of the bridge experience an increasing compressive load up to the mid-span of the bridge, the measurements shown in Fig. 11 (left) describe the correct general trend. That this trend is not fully linear around measurement position 68 has to be devoted to the influence of the 1.3 ton inspection trolley that has been positioned around that location. Furthermore it has to be considered that MikroMach is sensitive to a variety of influences including residual stresses, stresses from net weight and fatigue damage such as dislocation rearrangements. Differentiation of those influences requires further measurements to be made including a repetition of the measurements with varying trolley positions. Also, supporting on-site methods like hardness measurements and chemical analysis of the surface could help to interpret and to explain the results. Finally a fatigue analysis to be performed will hopefully help to further differentiate the signals.

6 CONCLUSIONS

With the variety of established and emerging smart sensing and simulation technologies life cycle management of ageing infrastructure becomes feasible. This is specifically true for ferromagnetic steel infrastructure where electromagnetic monitoring techniques can be used to characterise the structural material's condition even before microcracking starts. In case no drawings of an infrastructure are available those can be generated by gradually monitoring the structure through visual imaging on a 2D and even 3D basis and generating a 3D model of the infrastructure in an even digital format. This digital format builds the basis of a modern platform for further life cycle assessment such as static and fatigue strength calculation. Through experimental validation, such as using a loads sensor based on optical fibre Bragg gratings, enhanced methods for generating fatigue data such as with the PhyBaL method, and an electromagnetic testing equipment for characterising a materials damage condition at microscopic level, those models can be continuously updated and will hence serve from a prediction point of view to assess the infrastructure when which type of maintenance measure will have to be expected. This approach is currently validated specifically on a variety of steel bridges and may become a large step forward in enhancing life cycle management of ageing steel infrastructure.

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