Novel Means and Ways of Getting Structural Health Monitoring into Application

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ABSTRACT

Research and development of Structural Health Monitoring (SHM) has been around for decades now. However, with so much effort performed in the past, much more SHM application would have been expected. Reasons for this situation are various but one is certainly the diversity of subjects and topics in which SHM plays a role and vice versa. A way on how to grasp the diversity in SHM and to get it focused to some degree is to get the application of SHM to be shown based on demonstrators. SHM demonstrators is not something new. However, what often happens to those demonstrators is, that they are not used once the project they have been funded from has been completed. In addition to this, the demonstration usually turns up during the end of a project and this maybe even happening in a rush. This short period of time does often not even allow the outcome of the demonstrators to be sufficiently communicated with the true potential applicants, which may be an industry allowing the SHM technology to be commercialized.

An initiative has therefore been started out of Germany recently with international participation from Greece, Poland, South Korea and the USA, where available SHM demonstrators are extended in their use, such that data obtained from those can be shared with an international community or data can be generated, validated and disseminated with any SHM technology potential applicants want to get linked to the demonstrator with. So far 14 potential demonstrators ranging from aerospace over wind energy to civil engineering and others have been identified.

Within this paper the different demonstrators available so far are briefly introduced including their potential with data already available and the options for SHM technology providers, to get their technology applied, validated, and demonstrated in future actions. The network and hence platform for this SHM technology demonstration initiative will be generally opened to the general public and it is intended to demonstrate the application of SHM technology at various future scientific and technology trading events, would this be traditional conferences, symposia, fairs and possibly others.

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INTRODUCTION

SHM is now around for decades. Many definitions have been made, where a limited selection is given below:

D. Adams [1]*:*

1. Health monitoring is the **scientific process of non-destructively identifying four characteristics** related to the fitness of an engineered component (or system) as it operates: The **operational and environmental loads** that act on the component (or system)
2. The **mechanical damage** that is caused by the loading,
3. The **growth of damage** as the component (or system) operates, and
4. The **future performance** of the component (or system) as damage accumulates.

AISC/SAE [2]*:* Structural Health Monitoring is **the process of evaluating the integrity of structural elements** using calculation methods and onboard systems to as- sure the aircraft continued airworthiness from the structural standpoint, focusing on the **improvement of design, operation and maintenance.**

D. Balageas [3]*:* SHM aims **to give, at every moment during the life of a structure, a diagnosis of the ‚state' of the constituent materials**, of the different parts, and of the full assembly of these parts constituting the structure as a whole. The state of the structure must remain in the domain specified in the design, although this can be altered by normal ageing due to usage, by the action of the environment, and by accidental events. Thanks to the time-dimension of monitoring, which makes it possible to consider the full history database of the structure, and with the help of usage monitoring, it can also provide a prognosis (evolution of damage, residual life, etc.).

C. Boller [4]: SHM is **the integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be recorded, analysed, localised and predicted** in a way that non-destructive testing becomes an integral part of the structure.

V. Giurgiutiu [5]: SHM is an **emerging research area with multiple applications**. SHM **assesses the state of structural health and, through appropriate data processing and interpretation, may predict the remaining life of a structure.**

T. Stepinski, T. Uhl and W. Staszewski [6]: SHM **is an interdisciplinary field that deals with innovative methods of monitoring structural safety, integrity and performance without affecting the structure itself or particularly impairing its operation.** SHM utilizes several types of sensors – embedded in or attached to – a structure to detect the presence, location, severity and consequence of damage. SHM integrated non-destructive evaluation (NDE) techniques using remote sensing and smart materials to create smart self-monitoring structures characterized by an increased reliability and long life. SHM primarily applies to systems with critical demands concerning performance, where classical onsite assessment is related to high costs, is difficult or even impossible.

All of these definitions, and there may be even much more, have partially commonalities but are also driven by different foci. However, all have been defined out of the SHM community, and the question is, how could this all be brought under a common ‘umbrella’. One challenge in that regard is the breadth of topics being addressed ranging from ‘loads’ to ‘future performance’ (D. Adams) in general. While analysis is a prerequisite in all of the definitions, prognostics explicitly is mentioned in most of the definitions (all except AISC/SAE). Keeping this as it is, would mean, that the damage tolerance concepts developed more than 70 years ago would represent SHM. They certainly do. However, SHM is one step further ahead and this is the ability to let sensing and possibly also actuation devices to become an integral part of a structure (C. Boller, T. Stepinski et al.).

THE SHM PROCESS CHAIN

Trying to get this ‘umbrella’ established may lead to a process chain as shown in Fig. 1. Considering an engineering structure, the design of a structure starts by defining the structure’s operational loads. It further requires its geometry to be shaped, defined by the structure’s functionality and architectural design. With this the structure’s loading can be determined usually expressed in terms of stresses and strains. Since operational loads are repetitive, material’s fatigue applies, which leads to a structure’s degradation and hence damage. It is here where the application of the damage tolerance principle starts and where prognosis of the degradation process as well as inspection are required, the latter being usually performed in terms of non-destructive testing (NDT). Since this inspection process can become time consuming and costly, automation is an option to consider, which leads to what the scientific community has considered as SHM system solutions. Although SHM as an expression only turns up with the very last element of the process chain - because all other elements have to be considered as state-of-the-art in structural design - SHM itself has to be seen to encompass the complete process chain shown in Fig. 1. A structure’s health has to be seen from a holistic view.

The design of engineering structures today is increasingly performed on a numerical and hence digital basis. Various tools have been developed in the past, that allow the different process elements shown in Fig. 1 to be simulated. However, what is still missing is a ‘backbone’, that allows the different simulation tools to be integrated to an entity, that will allow SHM to be performed from its holistic point of view. A means on how to get this realized may be given through what is characterized as a digital twin. In different sectors such developments are making good progress, such as in civil engineering, where Building Information Modelling (BIM) is increasingly becoming a standard. However, those digital twins may just

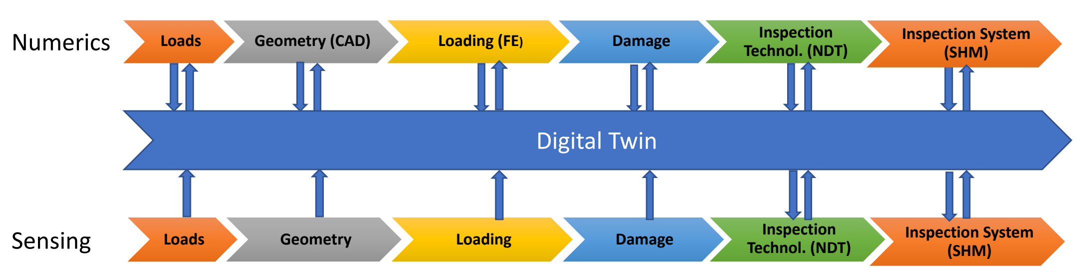

Figure 1. Process chain of holistic life cycle management in view of SHM

cover the first two to three elements of the above process chain, while an SHM-based digital twin may require much more. It is therefore a future task and challenge for the SHM community, to get such digital twins realized.

Realization of an SHM-based digital twin does allow all the sensing information provided by different sensors associated with the structure to be integrated, as indicated in Fig. 1. This also indicates that all the sensing being related to those different process elements, would that be loads, geometry, loading or damage information are contributions, specifically associated to developments in SHM. It has to be noted in that context, that data is mainly a one-way flow. However, when it comes to the application of NDT and SHM systems, information with respect to a tolerable degradation to be monitored has to flow to those systems such that the systems can reply if the degradation has been achieved or not.

SHM APPLICATION ENHANCEMENT

There is no doubt that SHM has found its way into application already since a long time. Vibration monitoring systems in structures have been established since decades would this be rotating machinery [7] or civil infrastructure such as bridges [8]. Also loads monitoring has been introduced in aircraft [9] as well as in high performance marine structures [10]. A sector where SHM has gained a significant interest is wind energy generation [11]. The incredible boost in performance enhancement combined with limitations in knowledge of operational loads has driven the need for operational loads monitoring including the structural dynamic behaviour and with this the implementation of the respective sensors including the related signal processing and interpretation in the sense of prognostics. Different companies have been established dealing with sensors would those be related to fibre optics, piezoelectrics or even electromagnetism. The need for demonstrating the applicability of SHM has been early recognized within the Internat. Workshop on SHM (IWSHM) at Stanford University. Already years ago, a special session named ‘SHM in Action’ has been introduced at IWSHM and others, along which R&D groups as well as industrial companies have been given the chance to get their developments as well as products demonstrated. However, this has been limited to the demonstration of some single technology. What has been missing so far is the demonstration of SHM in the wider context as shown along Fig. 1, which might be the challenge for the future of this special session.

A big need for SHM has recently arisen through the increasing number of ageing infrastructure and this specifically in the context of civil engineering where bridges have become a major issue. Much of this infrastructure has been designed 50 or more years ago, where much less of a structure’s loading or a material’s degradation behaviour has been known. As a consequence, safety factors had to be set high such that structural integrity would not be compromised. However, with the additional knowledge and specifically information generated through SHM, those safety factors may be reduced without compromising a structure’s integrity and safety, allowing an infrastructure’s life cycle to be better managed than this has been done before. This may lead to operational lifetime extensions and new maintenance concepts, that may significantly reduce an infrastructure’s operational cost and may have additional positive implications on sustainability with respect to natural resources savings and environmental impacts. A case with respect to a listed steel bridge in Hamburg/Germany has shown that the effort in maintenance of the bridge could already be reduced by around a factor of 10 through simply introducing a loads monitoring system only [12].

Although a lot of SHM application has been shown, this could be further enhanced if the breadth of SHM could be demonstrated in the sense of the process chain shown in Fig. 1. In view of this breadth and the variety of single technologies being developed, technology demonstration becomes of a very significant importance in this case. So far, SHM technology demonstrations have been performed along various R&D projects performed, however, the demonstrators having been developed have mainly remained as single cases, possibly moth-balled at the end of the project if not even scrapped. Many of those demonstrators could possibly have been used for further SHM-related purposes and be further developed, would those have been made available to a broader public. An initiative named *SHM into Application!* has therefore currently been established out of Germany and extended to an international community consisting of different institutions providing SHM-related demonstrators to any SHM technology providers, academic as well as industrial, to get their technology demonstrated and validated. The idea is to get those demonstrators shown in reality or in virtue at the next European Workshop on SHM (EWSHM), due in Potsdam/Germany in 2024 (www.ewshm2024.com) and possibly others, including the technologies already implemented into those demonstrators and the additional options due to emerge. Participants of EWSHM 2024 should be inspired to get further ideas on how to get their technologies demonstrated and validated or possibly even further demonstrators proposed, which might be demonstrated at consecutive events such as IWSHM.

THE SHM INTO APPLICATION ! INITIATIVE

The 'SHM into Application !' initiative is a nucleus of 10 organizations including AGH Univ. of Science and Technology Cracow/Poland (W. Staszweski & T. Uhl), BAM Berlin/Germany (E. Niederleithinger & J. Prager), Goethe Univ. Frankfurt M./Germany (J. Moll), Korean Advanced Inst. of Science & Technology (KAIST) Daejeon/South Korea (H. Sohn), Missouri Univ. of Science & Technology Rolla/USA (G. Chen), Saarland Univ. Saarbrücken/Germany (C. Boller), Stanford Univ. Stanford/USA (F.-K. Chang), Techn. Univ. Clausthal/Germany (P. Wierach), Techn. Univ. Munich/Germany (C. Grosse) and Univ. of Patras/Greece (D. Saravanos). Various of those organizations have already announced that they will get hardware demonstrators made available at EWSHM 2024 being related to aerospace and civil engineering applications.

With respect to aerospace this includes an Airbus A350 type fuselage section as a full-scale hardware demonstrator of a complex structure mainly made of CFRP and added by a variety of aluminum fittings. It is equipped with a huge network of piezoelectric transducers, which are integrated/adapted into/onto the structure at damage critical locations, allowing acoustic waves, and here specifically guided ultrasonic waves, to be used for the monitoring purpose. The other aerospace related demonstrator is an air brake made from a composite material including artificial flaws, which has been used for merging and visualizing monitored data also in the sense of augmented reality. The two demonstrators are shown in Fig. 2.

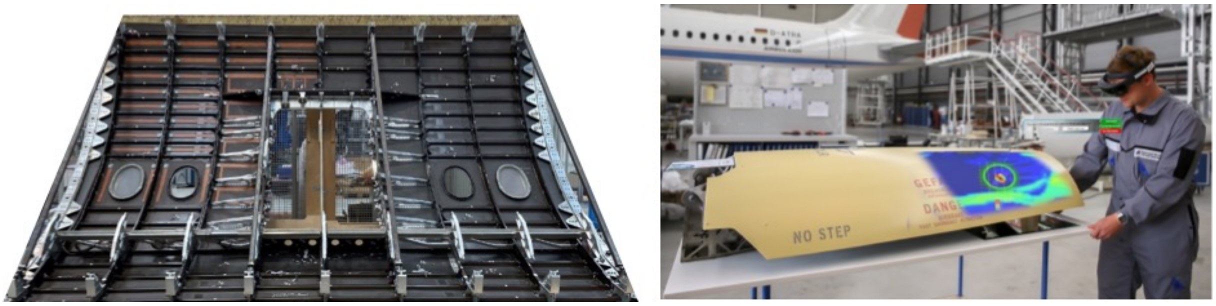

Figure 2: Aerospace related demonstrators: fuselage section of an Airbus A350 type (left) and composite air brake (right)

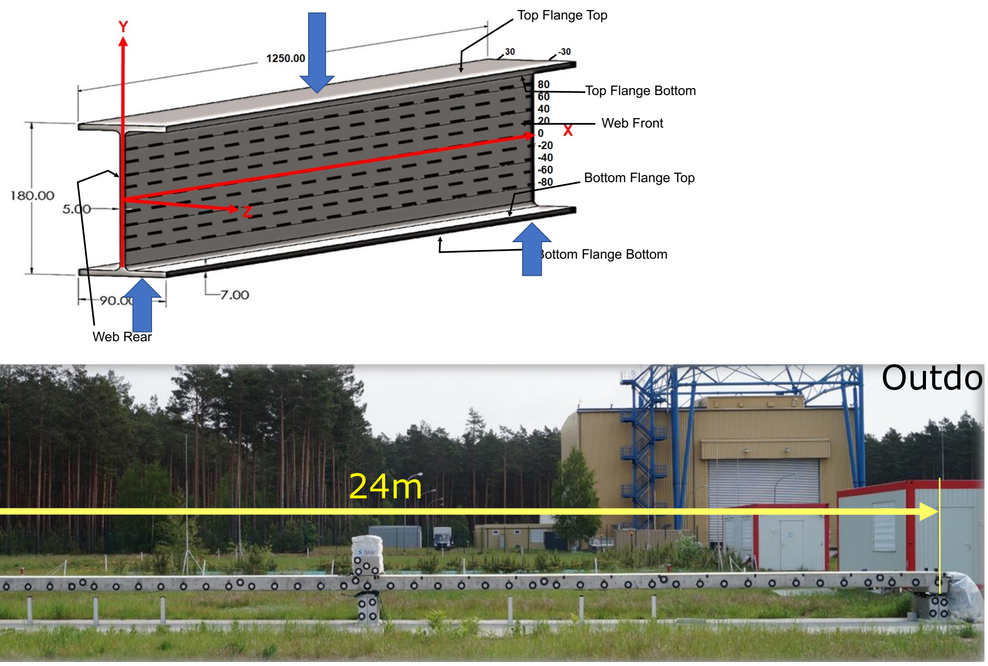

Figure 3: Civil engineering demonstrators: steel beam under 3-point bending (top) and reinforced concrete beam with variable loading (bottom)

As regards the civil engineering applications, the two demonstrators shown in Fig. 3 will be presented at least at EWSHM 2024. These include a 3-point bent steel beam, for which a variety of data has been generated including a visual 3D scan of the geometry, ultrasonic stress measurements and a variety of magnetic measurements allowing the material's condition to be assessed. The data is stored in a database such that the data formats are compatible to be used in the sense of a digital twin in the end. The other civil engineering demonstrator is a 24 m long concrete beam, that can be equipped with a variety of sensors would those monitor loads, deformation or any type of degradation resulting from variable loads to be applied.

There are further demonstrators proposed emerging from the wind energy sector, which can not be demonstrated in hardware at the different workshops and conferences, but which may be demonstrated from its data platform, would it be in terms of digital modelling and data remotely monitored in real time and merged in the sense of a digital twin. A demonstrator to be shown at EWSHM 2024 is a pressurized tank made of CFRP and aluminum liner to be considered hydrogen storage.

It is also important to mention numeric simulation platforms to be another form of demonstrating the application of SHM. A first attempt in that regard has been with the introduction of the Open Guided Waves platform [13,14]. The central idea and motivation are to make experimental data available to a general public such that algorithms developed can get validated. The experience gathered with this so far could possibly serve to explore on how such a platform could be expanded to even other monitoring techniques or numerical simulation tools to be provided. This could lead to a service providing numerical simulations for parties being interested in potential SHM applications.

A part of the demonstrations also includes robotic inspection systems such as crawlers and micro aerial vehicles being equipped with a variety of different sensing techniques allowing visual, thermal, radar and possibly other inspections [15]. It is currently explored how far those robotic systems could be used in combination with the hardware demonstrators referenced above and due to be shown at EWSHM 2024.

Finally, there is a demonstrator included, which is used for process control of additively manufactured parts [16]. This sounds somehow strange within the context of SHM but becomes relevant once a life cycle documentation of a structural component may be considered, documenting a component from its manufacture up to scrap.

This portfolio of demonstrators presented here has just to be considered as a start and is open for any further extensions.

CONCLUSION

If SHM is considered to cover such a breadth of elements as shown in Fig. 1 it is possibly essential, that at least a set of 'living demonstrators' do exist, that increasingly allow innovations developed within the different process elements to be part in view of SHM. This may include new types of sensors would those be used for loads, geometry or degradation monitoring. These sensors could even be based on well known physical principles already applied in SHM but where the sensing technology might have demonstrated improvements in terms of systems' integration, miniaturization, resolution, cost, reliability and possibly more. A huge field is also sensor signal processing, where new algorithms are worth a try before they might become part of an SHM system. This might be also associated with what is currently ongoing in the field of artificial intelligence. Similar trends have to be seen with respect to numerical simulation tools, where continuous improvements can be seen that require a validation. Nothing is better in that case than having the same demonstrator for validation that would allow an improvement made to become clearly apparent. The emerging issue of digital twins is a process, which will require a decent amount of time until being fully established within the scope of engineering structures' life cycle management including SHM. The different sensors, tools and algorithms, which will have to interact will need a careful development of the data interfaces, that will allow data to flow smoothly. Again, established technology demonstrators could serve as a clear reference, also with respect to SHM related technology being then transitioned into further applications. Finally, long lasting technology demonstrators can help to keep technology discussion ongoing within the SHM community in case the demonstrator might move from one scientific conference to another. Furthermore, it could also move to trade fairs, more addressing the application-oriented industries. However, what this initiative needs is a supportive community of enthusiasts as well as the financial support, that more than pay off the rewards the initiative may provide.

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