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Integration of Non-Destructive Evaluation based Ultrasonic Simulation (INDEUS) – A Means for Simulation in SHM

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Abstract

Simulation has become an unavoidable prerequisite in engineering and science today. In non-destructive evaluation (NDE) simulation has gained highest importance with respect to determining the probability of detection (POD) of an inspection method. POD in NDE is optimised in a way that the best sensor positions as well as sensor tracking paths are found through simulation. In NDE a sensor can be moved around the component to be inspected until a full capture of the component is achieved. However, with structural health monitoring (SHM) no movement of the transducers is possible in case those become an integral part of the component considered. Hence simulation becomes even more essential in the case of SHM.

The paper provides an insight into the INDEUS project briefly describing the concept of the simulation platform, the different simulation tools involved, the requirements and options for further extension and the different test cases applied for validation so far with the target to simulate complex structures such as bridges, aircraft components and others made of metallic and polymer-based monolithic and composite materials. Results obtained from the simulation platform established within the INDEUS project will be related to detecting probability of damage for a given loading condition and structure, the propagation of guided waves due to damage in a complex metallic component and the determination of an optimum transducer network allowing a tolerable damage to be detected by an SHM system reliably.

Keywords: Simulation, Ultrasonics, Guided Waves, Structures, Damage detection, Transducer optimisation

1. INTRODUCTION

Simulation has become an unavoidable prerequisite in engineering and science today. In non-destructive evaluation (NDE) simulation has gained highest importance with respect to determining the probability of detection (POD) of an inspection method. POD in NDE is optimised in a way that the best sensor positions as well as sensor tracking paths are found through simulation. In NDE a sensor can be moved around the component to be inspected until a full capture of the component is achieved. However, with structural health monitoring

(SHM) no movement of the transducers may be possible in case those become an integral part of the component considered. Hence simulation becomes even absolutely essential because it is only possible by this means to determine a transducer network optimum configuration. While an NDT inspector can take an m number of samples until he/she is satisfied with the result and the highest POD is achieved there only exists one option/solution that can be realised in SHM since the transducers are fixed and cannot be moved around anymore like this is possible in classical NDT. The $n = m - 1$ additional options which classical manpower driven NDT has, can therefore only be compensated through simulation in the case an SHM solution should work as well as a classical NDT inspection does.
SHM is beneficially applied when the structure being considered has been designed damage tolerant and has therefore to be inspected at defined intervals. In that case it is important that the type and size of non-critical damage allowed in the structure is reliably detected by a network of transducers representing an SHM system, where this SHM system has been determined through an optimisation process based on simulation. This fact underlines the importance of simulation in SHM and the need for this to be provided adequately.
Within the Indo-German project INDEUS a first attempt has been made in establishing an NDE-based simulation platform that can also be used for SHM purposes. This platform looks at different tools allowing ultrasonic as well as guided waves to be simulated and how those can be linked to operational loads and fatigue life evaluation processes. A major objective along the project is to provide simulation tools that are able to operate close to real time even for big and complex structures made from isotropic and anisotropic materials. This requires hybrid simulation tools to be used that will look at the details around the specific locations of interest using tools such as based on spectral FEM on the one side while in the remaining locations on the other side approximation procedures such as ray tracing may be sufficient to be used.

2. THE STRUCTURAL ASSESSMENT PROCESS CHAIN

When a damage tolerant engineering structure undergoes a design and also an operational life cycle process it does follow a complete process chain for which a general example is provided in Fig. 1 below, which can also be considered as an SHM validation and verification process chain.

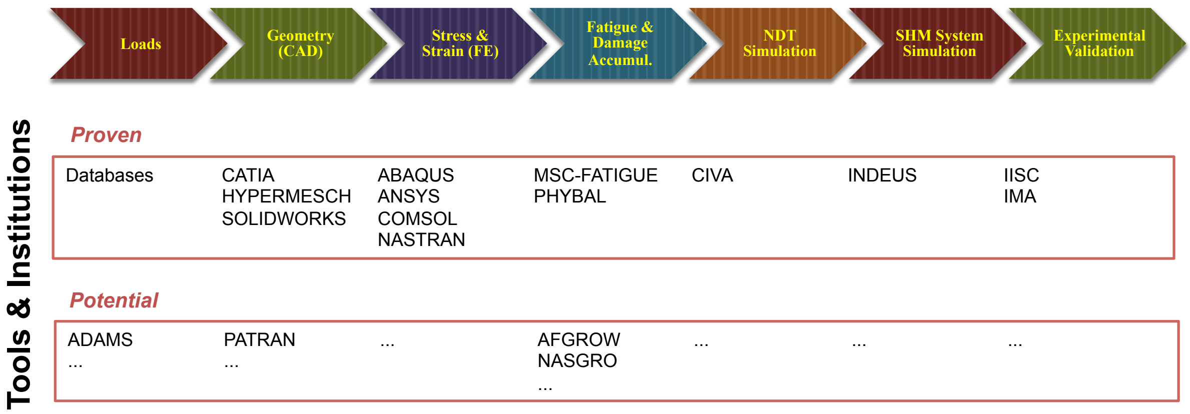

Figure 1: SHM validation and verification process chain

Like with every structure to be designed it starts with the loads to be applied, being defined by the structure's mission such as a load transfer from location A to location B and the operational conditions (i.e. time, acceleration, maneuvers, etc.) this is going to happen under. This is done in conjunction with the structure's shape, which is initially defined through a CAD design driven by a designer or architect. This is then followed by an FE analysis, where the stresses and strains within the structure considered are calculated considering the loads having been determined initially versus the shape given to the structure and the resulting stress and strain concentrations to occur along the different notches resulting from the structure's shape. Along this analysis already a first comparison is made as to which degree the applied stresses and strains concentrating at the notches do already exceed the allowable stresses of the structural material having been chosen. In case of such an exceedance the structural shape and/or the material has to be changed such that the applied stresses and strains become smaller than the allowable stresses and strains. The same iteration approach has to be made with respect to fatigue analysis where the operational load sequence (spectrum) has to be considered as well as the fatigue strengths being lower than the tensile strengths and where different simulation tools have been made available over the years. These tools do not only allow a fatigue life to be determined but also damage (i.e. crack) propagation to be simulated as well as the stress and strain distributions within the complete structure considered resulting from the respective damage condition considered. Since the level of stresses and strains applied at each load cycle can be numerically related to a damage occurring at virtually any location considered on the structure this damage information can be literally accumulated over the number of load cycles applied as well as the complete structure, which results in a map showing the probability of damage along the structure considered. This information is important because it indicates at which locations of the structure damage (i.e. a crack) is most likely to occur which are then the locations where the respective SHM considerations and analyses then do start from a simulation point of view.

Since SHM can be considered as a certain type of NDT and vice versa it is useful to consider NDT simulation tools such as being currently developed and made available in different regards. Those tools can be used to get a first idea on where to place the transducers for an SHM system best. However, for the final optimisation and the resulting sensor signal processing specific codes are required which have been mainly realised or are under development mainly on an 'individual' and hence specific basis, such as the simulation tools developed under the INDEUS project and being further referenced below.

The lower part of Fig. 1 also makes reference to a selection of simulation tools being specifically associated with the different steps of the process chain addressed. Most of these tools are operating individually with respect to the specific process block considered. It has been the intention of the INDEUS project to initiate a process on how to get these tools merged to a simulation environment keeping in mind, that this is an ongoing process that will have to and must last beyond the INDEUS project to have the appropriate scientific impact. For that reason different simulation cases have been developed which have also been partially verified experimentally and which will be touched upon on a general basis in the following being also described in further details in other papers presented along EWSHM 2016 [1-5].

3. CLASSICAL FATIGUE ANALYSIS

Classical fatigue and fracture analysis such as based on the use of Rainflow load cycle counting, materials or structures data for cyclic loading, Palmgren-Miner's rule and linear elastic or elastic-plastic fracture mechanics combined with stress-strain-analysis based on finite element (FE) simulations are indispensable tools to obtain an understanding of a structure's stress and strain distribution as well as the distribution of damage accumulated. Although knowing that the result obtained in quantitative terms may not be correct this result may still have a value as it indicates at which locations damage may accumulate most. This information is important since it indicates which locations require the highest attention in terms of analysis and hence SHM. Within the INDEUS project a stiffened panel has been analysed. Fig. 2 shows the stress distribution on the left hand side and a resulting probability of damage on the right hand side respectively. It can be seen that a damage is more likely to occur in the panel skin while the stiffeners show a lower probability of damage. The other differences in probability of damage within the skin specifically result from the boundary conditions set within the simulation model. Hence when a crack may emerge from the rivets that join the stringer with the skin the crack may first propagate slowly before it enhances its growth rate due to increasing length and operation in the field of higher probability of damage. This leads to the distributions as shown in Fig. 3 for the stress distribution (left) and probability of damage (right).

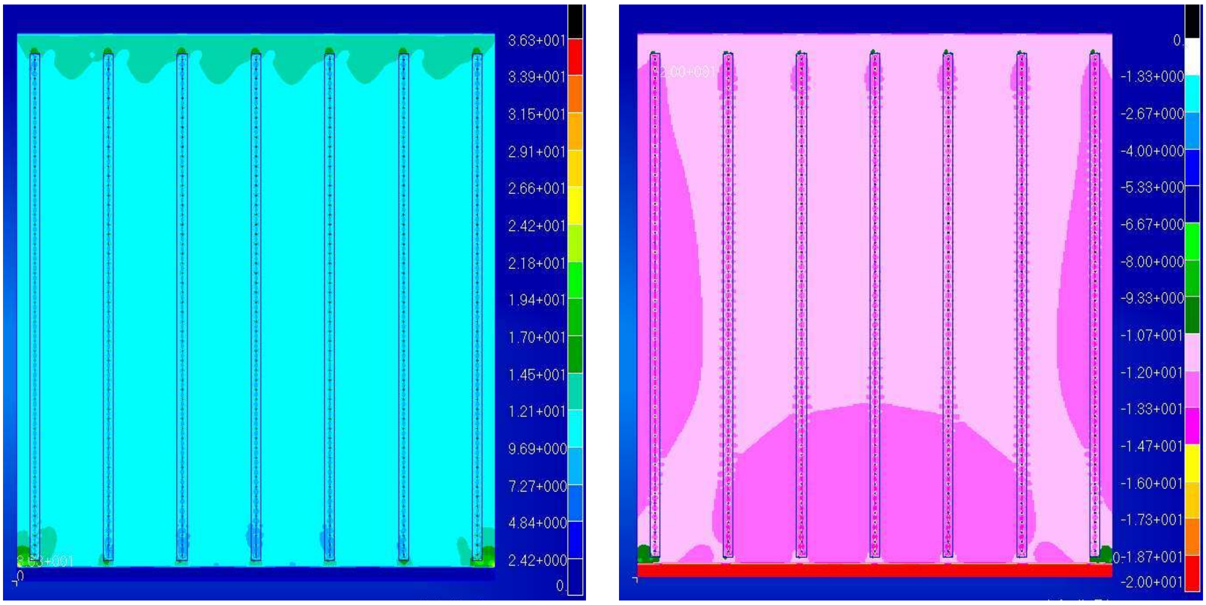

Figure 2: Simulation of a stiffened panel in terms of stress distribution (left) and probability of damage (right)

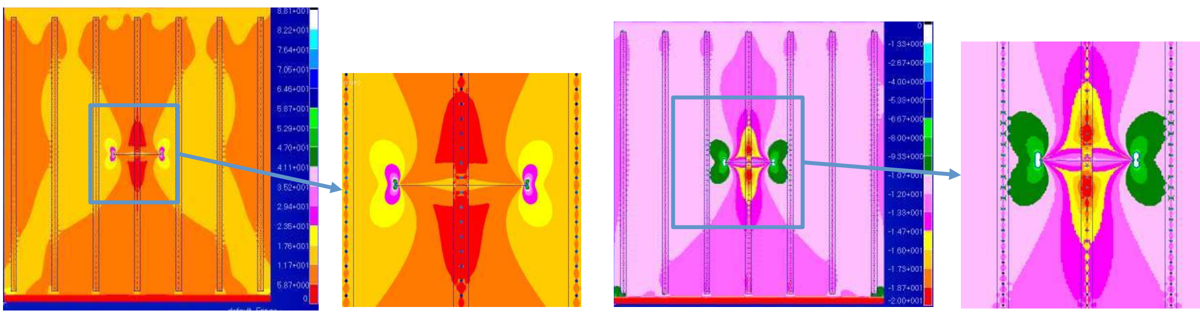
Figure 3: Simulation of a stiffened panel with a crack in terms of stress distribution (left) and probability of damage (right)

What can be specifically seen from the distributions in Fig. 3 is the strong differentiation between what is ongoing close to the crack and the rest of the structure. This differentiation is an essential information with regard to a follow-on simulation related to SHM.

4. HYBRID APPROACHES FOR SHM SIMULATION

SHM is based on physical principles with regard to mechanics, acoustics, electromagnetics and others, which are generally also applied in NDT. One of them being highly popular in SHM is the use of guided elastic waves. Frequencies being considered are in the range of hundreds of KHz to MHz which require a conventional FE simulation to become highly complex and time consuming when a large and complex structure is analysed with regard to guided waves travelling through this structure. However, simulations when being considered attractive are requested to operate near to real time nowadays. In guided wave SHM this can only be achieved through a hybrid approach so far. A hybrid approach is principally based on the fact that in areas of lesser relevance approximation solutions can be used while a detailed analysis is only done in the areas of high relevance hence areas where damage is likely to occur. Fig. 4 shows the cracked panel discussed before and how the respective transducers are positioned best using an analytic ray tracing approach as a first step. From this approach it can be determined which type of guided wave hits the area of interest, being most likely the area where damage accumulates most and is the incubator for a damage/crack to grow. This area is the area of specific interest and where a detailed FE simulation is required to understand the details of the simulation.

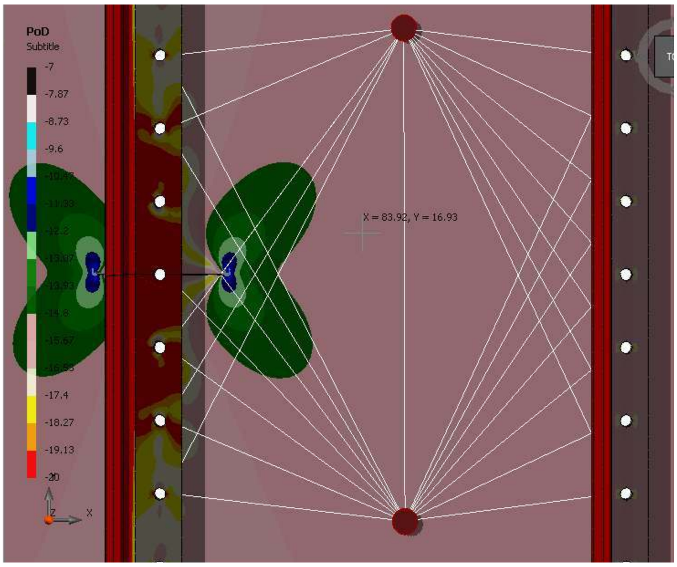

Figure 4: Guided wave transmitter and receiver placement analysis based on ray tracing

A selection of different analytical/semi-analytical, numerical and hybrid approaches to be used in guided wave simulation is provided in Fig. 5 where more approaches may be included that have not been known so far.

5. SIMULATION AND VALIDATION CASES

Since establishing the INDEUS project a number of different simulation cases with increasing complexity have been analysed within but increasingly also outside the INDEUS project. A first comparatively simple case has been based on an aluminium plate with three holes and possible cracking between two of the holes as described in [6] and shown in Fig. 6 respectively. The simulation tool having been used in this case was COMSOL. The left hand figure shows the configuration of the specimen while the right hand figure shows a so called differential plot which is the amplitude difference of the guided wave signal snapshot between the pristine and the cracked condition. This plot provides an indication at which location the difference in guided wave signal is specifically strong and where it might be specifically worth considering transducers to be positioned that will detect a tolerable damage defined reliably. What turns out in that case is that the sensors have to be fairly close to the damage itself, an interesting result that requests more variations to be simulated in the future.

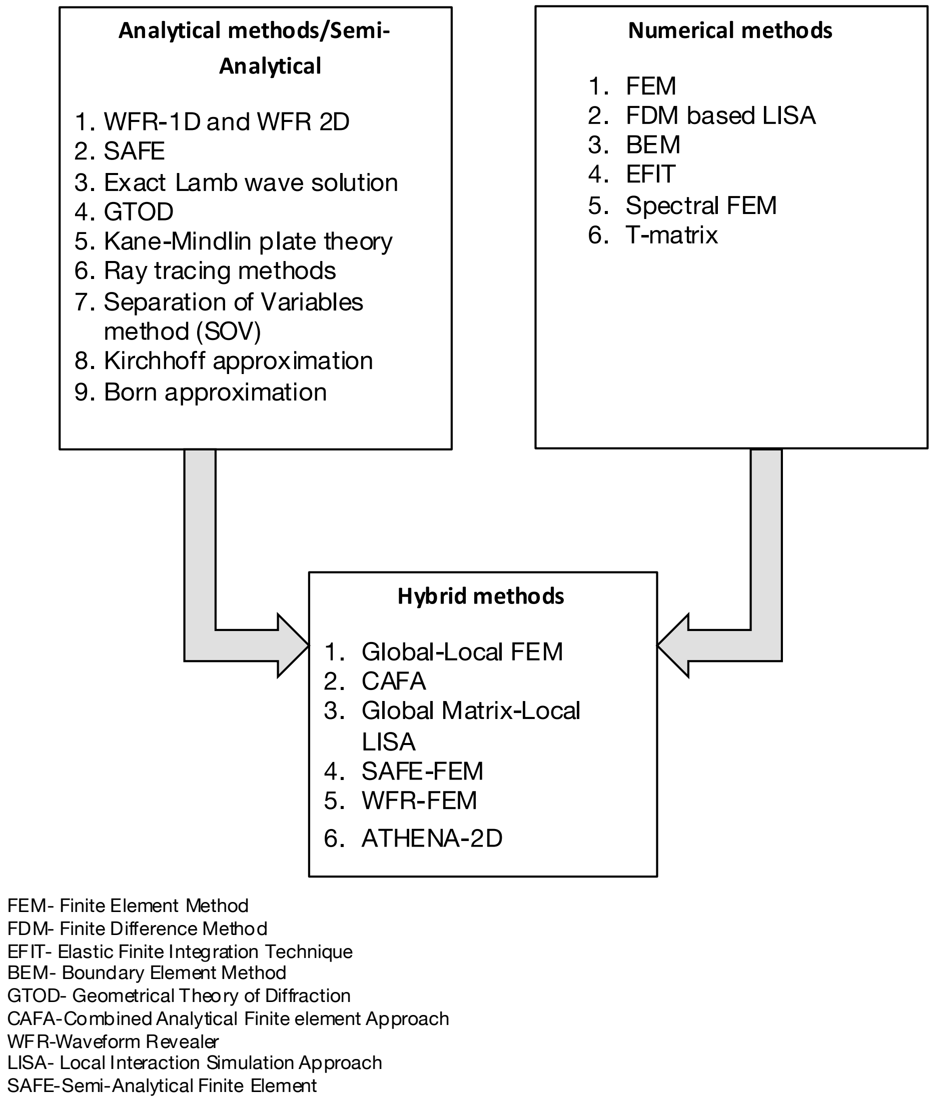

Figure 5: Hybrid methods for guided wave SHM modeling

Another simulation example of an aircraft aluminium panel where ABAQUS has been used as a tool is shown in Fig. 7 and Table 1 respectively [7]. The panel was 310 mm wide, 225 mm tall and 2.77 mm thick in size. For different crack sizes the amplitude change between the pristine and damaged condition has been determined and different classifications in amplitude change and hence damage detectability have been made as can be seen from the results for a 12 and 20 mm crack length where the classification codes have been provided in

Table 1. Again from the results it becomes obvious that the area of reliable detection is very limited, although the sensor network is quite dense.

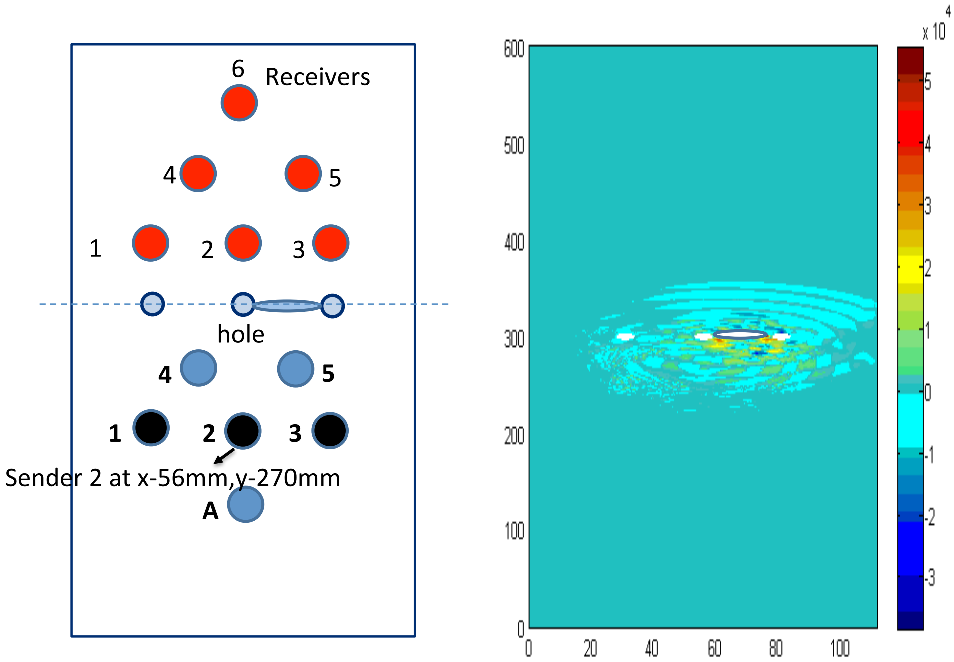

Figure 6: Three hole aluminium plate with crack: transducer configuration with three actuators used shown in black (left) and resulting guided wave differential plot (right)

A further validation case again within the INDEUS project has been the stiffened panel described above. Here differential plots have been obtained like the one shown in Fig. 8 below.

Amplitude Change	**Classification**	**Color Code**
< 0.02%	Bad	Red
0.02% – 0.04%	Poor	Purple
0.04% – 0.06%	Medium	Orange
0.06% – 0.08%	Good	Green
>0.08%	Excellent	Blue

Table 1: Detectability quantification

The current platform and the data having been made available do allow for further variations to be made with respect to transducer placement and input signal generation as well as extensions in general. Other activities include the consideration of composite materials. All of this is still subject of exploration during the remainder of the INDEUS project.

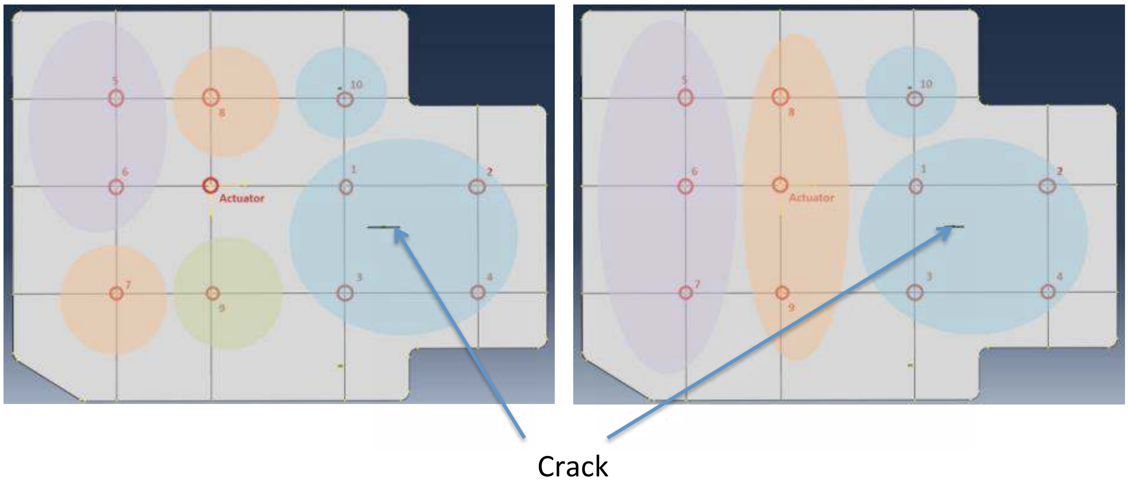

Figure 7: Detectability map of cracked panel: 20 mm long crack (left) and 12 mm long crack (right)

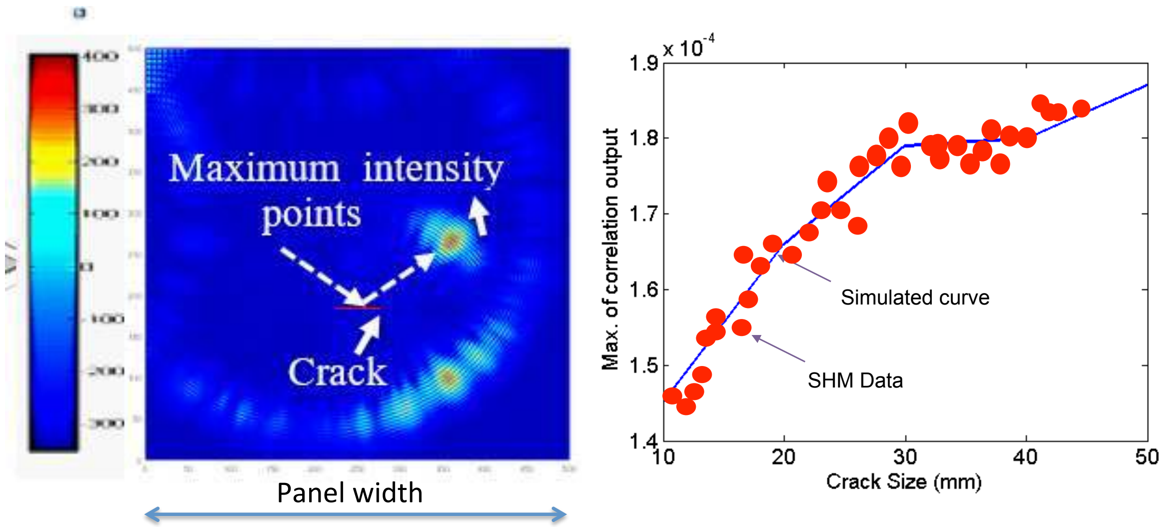

Figure 8: Simulation results for stiffened aluminium panel: Differential plot for transducer location placement (left) and online experimental verification of simulated crack propagation curve (right)

6. CONCLUSIONS

It is no question that there is a need for simulation within SHM. There are many different simulation tools available that allow the SHM task to be met to the one or the other degree. However, those tools need to be better linked such that they allow for an efficient and reliable SHM system to be designed in accordance to the engineering structure being considered. With the INDEUS project a first approach has been done in that regard but there is much more required to get this realised to a complete satisfaction if this can be ever stated in that way at all. The first results obtained show some interesting conclusions to be drawn with regard to the selection of transducer patterns and how close the sensors have to be to get a damage monitored reliably. This result raises interesting questions with regard to what influence different actuator positions as well as actuation signals could have. It further leads to new ideas with regard to unconventional and new sensor shapes as well as monitoring principles being other than guided elastic waves only. With the INDEUS project a first step has therefore been done with regard to verification and validation of SHM systems for damage tolerant structures.

ACKNOWLEDGEMENT

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