Digital Twin Deep Link: Physics Based Model with Scientific Machine Learning for Simultaneous Crack and Wave Propagation

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ABSTRACT

The integration of Digital Twin technology with Physics based models and Scientific Machine Learning (SciML) offers a transformative approach for Nondestructive Evolution (NDE) and Structural Health Monitoring (SHM). Detection and prediction of crack evolution under local stress through wave propagation demands physics-based understanding of crack-wave interaction. Traditional computational methods struggle to simultaneously capture crack growth dynamics and guided wave interactions due to the complexities of remeshing and high computational costs. The study demonstrates the simultaneous simulation of crack propagation and guided wave interactions without requiring mesh updates. Further, by leveraging physics-informed neural networks (PINNs) under SciML approaches, a Digital Twin framework can bridge this gap, providing real-time, data-driven insights into Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE). This study presents a Digital Twin Deep Link framework that coupled physics-based models with SciML to accurately predict crack initiation, growth patterns, and guided wave interactions in stiffened structures. Case studies illustrate how physics-informed AI enables the identification of crack signatures in sensor data, providing a robust mechanism for defect detection and material state assessment. The results highlight the potential of SciML-powered Digital Twins in SHM and NDE, paving the way for AI-driven diagnostics and autonomous monitoring systems.

INTRODUCTION

The reliability and service lifespan of structures, be it in aerospace, naval, civil or energy industry, have always been intertwined with predictive maintenance and early prediction of failure patterns. Extensive research efforts have been exerted towards the development of different Nondestructive Evaluation (NDE) techniques for the assessment and characterization of defects in structures. However, NDE alone lacks the

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functionality for real time monitoring and prognosis and is mostly limited to local applications. Digital Twin with a physics based deep learning can provide a one stop solution for continuous and real time assessment of structural components and help decide their service readiness, especially in aerospace and naval industries.

Digital Twins are categorized into different levels based on their sophistication and capabilities. Many Digital Twins deal with Level II (Informative Twin) to Level III (Predictive Twin). In previous work [1], the authors presented an implementation of Level III Twin. This work provides an advanced framework of the Predictive twin by incorporating physics-based analysis which creates the baseline for a Level IV Twin known as Comprehensive Twin. At Informative level, the Twin mostly incorporates data from sensors which provides real time understanding of the asset. Monitoring and diagnosis of the assets are performed at the next level which provides the current health status of the structure. Statistical analysis can be performed on sensor data to predict the damage characteristics. Further, this damage prediction is fed through physics-based structural analysis model (Peridynamics) combined with real time dynamic loading data. The continuous external loading which propagated damage, and the sensor activity, ultrasonic guided wave propagation, would be simulated simultaneously. This analysis would provide a more comprehensive understanding of dynamic structure. This makes the Uncertainty Quantification driven analysis much more accurate to predict the remaining useful life of the structural components. Thus, Level IV, Comprehensive Twin, can be realized and decision making for future operations would be achieved with minimal errors.

DIGITAL TWIN DEEP LINK

The goal of integrating physics-based models with scientific machine learning is achieved through the deep link software. The architecture of the Digital Twin is provided in Figure 1.

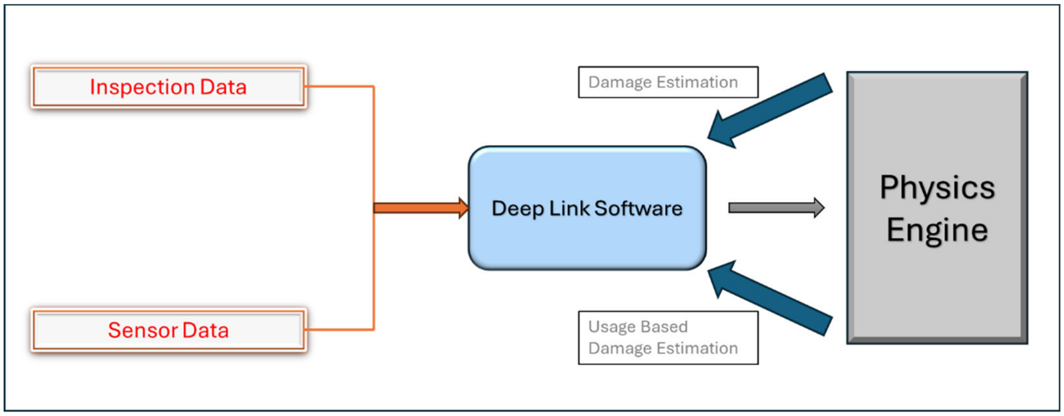


Figure 1 Digital Twin Deep Link architecture

The deep link software provides an interface for integration of all the modules of the Digital Twin. The user can choose different structures and the dataset of the sensors to run the analysis on. A dummy representation of the GUI (Graphical User Interrace) of the Deep Link software is shown in Figure 2. The work in Ref. [1] describes how the dataset is prepared based on the sensor data from previous experiments. A Machine Learning (ML) model is then developed from the understanding of the data. The employed ML model then estimates real time damage scenario. The study has been done using guided wave sensor data. In this study, the local sensor data is fused with global health monitoring data i.e. accelerometer, strain gauge. A numerical simulation is presented which can mimic the operational conditions of the structures.

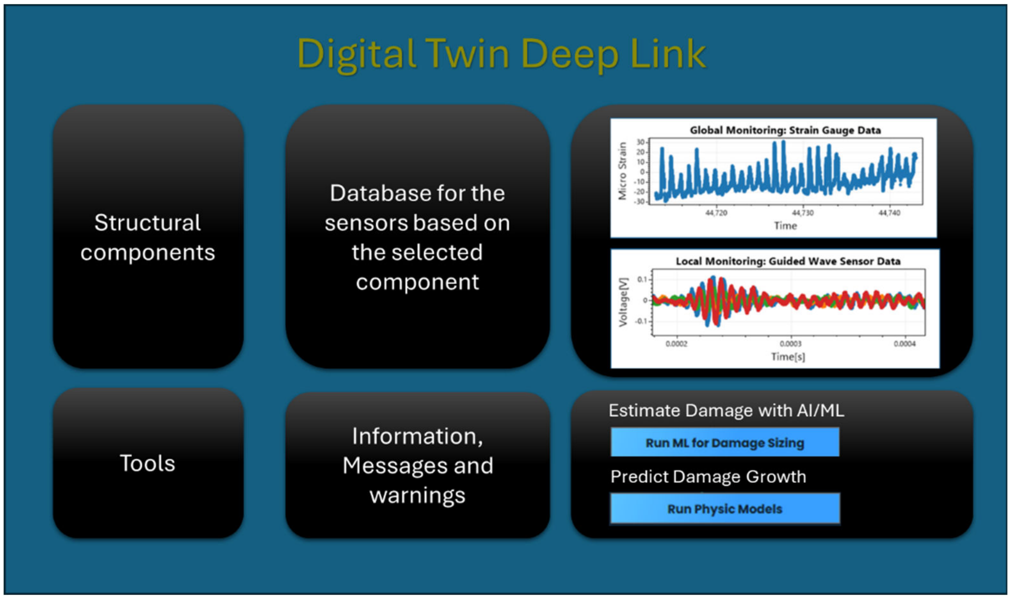


Figure 2 Dummy representation of GUI

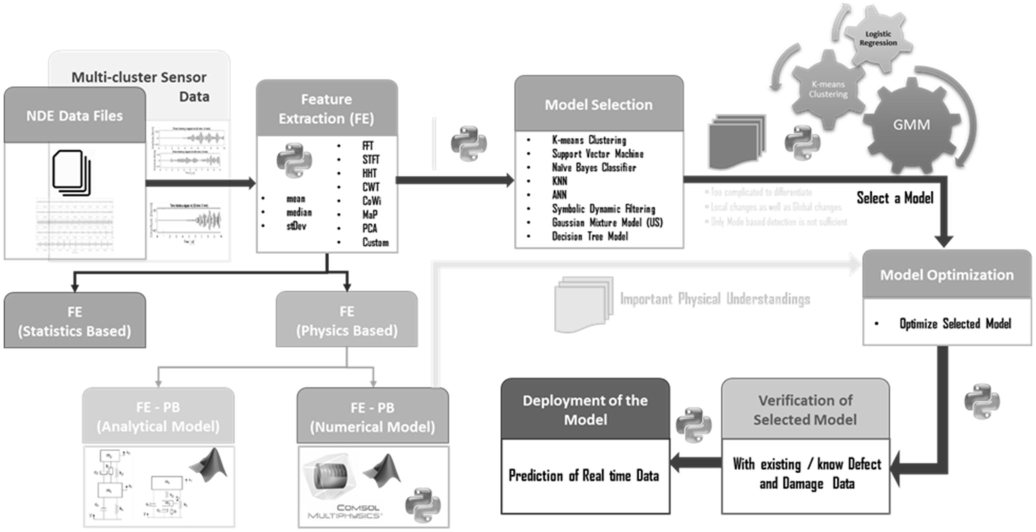


Figure 3 Machine Learning framework for SHM

The results of this simulation can then be utilized to further optimize the AI model. Figure 3 represents a schematic of the machine learning framework for structural health monitoring (SHM).

SIMULTANEOUS CRACK & GUIDED WAVE PROPAGATION

The estimated crack sizing data from the ML model can be utilized for damage growth simulations using any numerical methods. Many different computational and semi analytical methods have been utilized by researchers to investigate different phenomena of wave propagation and damage dynamics. However, traditional methods tend to be burdened with higher computational cost due to the need for remeshing for damage propagation simulation. Peridynamics (PD) [2], an alternative to continuum mechanics, can be an excellent method for tackling damage nucleation and propagation without remeshing the solution domain. Unlike the traditional methods where the governing equation is partial differential equation, PD uses force and displacement based integral equation as it's governing equation. This allows PD to model discontinuities without the need for remeshing the solution domain. PD has been applied for modeling different areas of ultrasonics wave modeling, particularly to understand the crack – wave interaction involving static crack as well as different stages of crack growth [3]. Here, the authors present the simultaneous simulation of crack propagation and ultrasonic wave propagation through the use of PD.

SIMULATION SETUP

The PD method used in this simulation consists of two theories, (a) bond-based PD (BBPD) and (b) state-based PD (SBPD). State-based is further divided into b.1) ordinary state-based and b.2) non-ordinary state-based. Bond – based PD is used in this work for the simultaneous simulation of crack propagation and guided wave propagation. The velocity – Verlet time integration method is utilized for the numerical calculations to determine the particle displacement at each time step. Related theories and mathematical equations can be found in Ref. [4].

The excitation of a structure with PZT is mimicked by placing a virtual PZT on the surface of a $200\,mm$ by $300\,mm$ Aluminum 6061-T6 plate (Table I). A 3.5 count $150\,kHz$ tone burst voltage profile was applied to the PZT to generate the Lamb. A square PZT of $2\,mm$ by $2\,mm$ with a maximum in plane radial displacement of $1\mu m$ is modeled in this numerical work. The displacement is enforced on the material points on the boundary of PZT and the material points inside the PZT are considered to have zero displacement.

TABLE I. ALUMINUM 6061-T6 MATERIAL PROPERTIES

Aluminum 6061-T6 material properties	
Density, ρ	$2700\ kg/m^3$
Young's Modulus, E	$69\ GPa$
Poisson's Ratio, ν	0.25 *for BBPD*

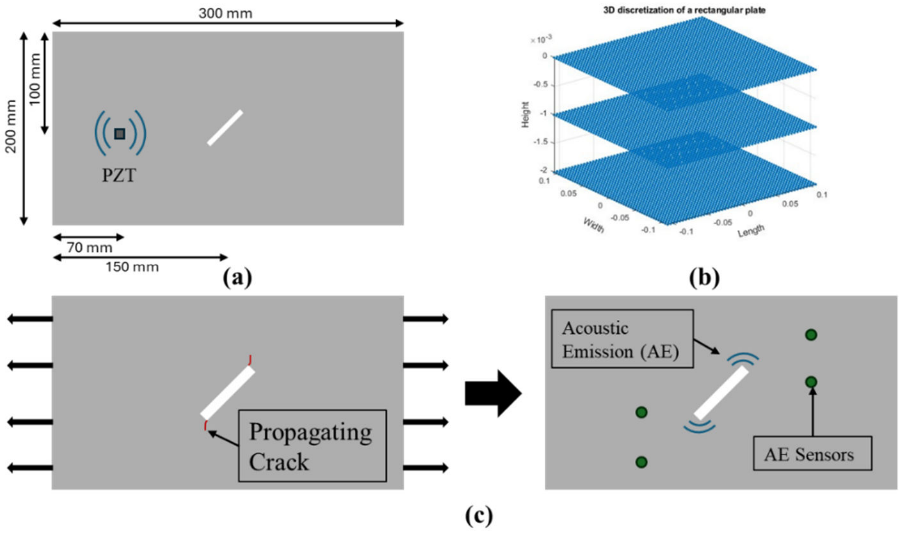


Figure 4 (a) Simultaneous crack - wave propagation, (b) 3D discretization, (c) Acoustic Emission (AE) mechanism

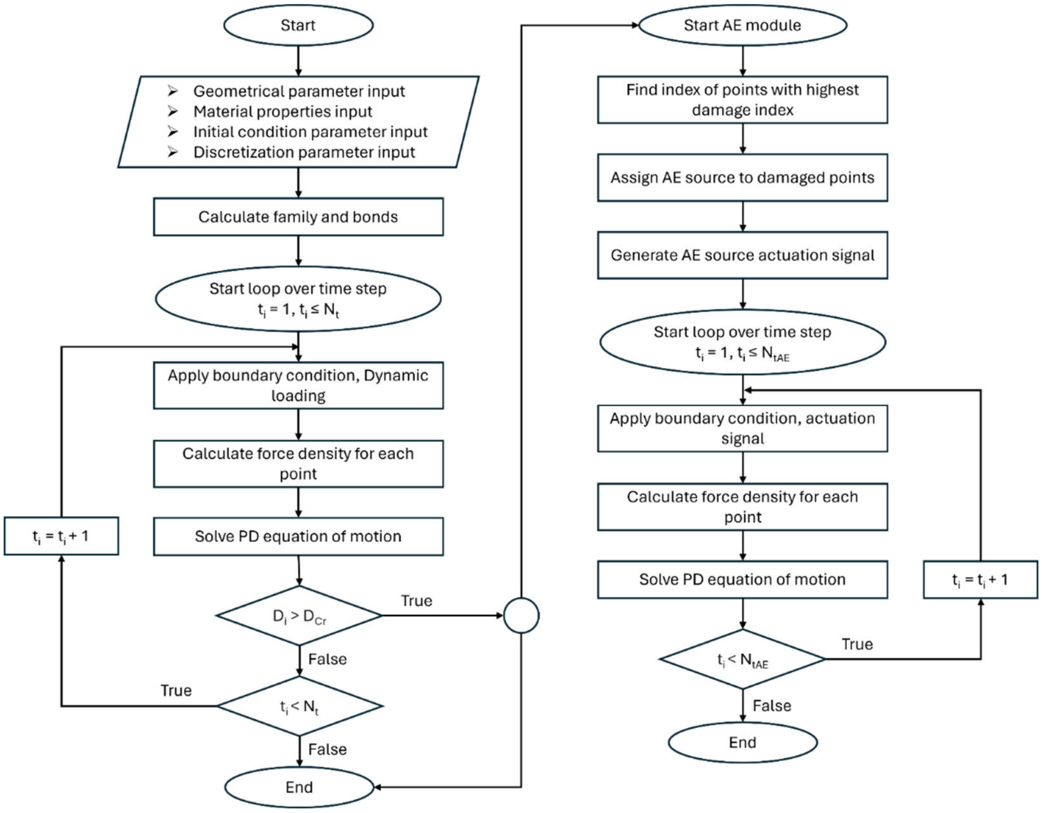


Figure 5 Simultaneous crack-wave propagation & AE source modeling flowchart

To understand the full wave profile, the spatial discretization needs to be at least one tenth of the wavelength and the temporal discretization needs to satisfy Courant–Friedrichs–Levy condition [5]. This study uses the spatial and temporal discretization of 1 mm and 10 ns respectively which satisfy both criteria. Thus, the number of material points turned out to be 60,000 on each layer of a pristine plate. After removing the points for a thorough thickness crack of 30 mm length and 3 mm width, the number of layer material points is 179676. Finally, the horizon size is determined to be 3.015 times the spatial discretization. For the loading boundary condition, a displacement boundary of 5 m/s is applied on the material points along the edges on Y axis. This simulation can be utilized to perform AE source modeling simulation. With damage growth the structures releases burst of energy as a form of AE. For the AE source modeling, similar configuration is used except here the PZT is removed and only tensile load is applied. When the Damage Index exceeds a certain value, it is considered that the crack propagation is initiated. The AE module then starts and a 450 kHz pulsed signal is generated at crack nucleation point for the AE energy release. Figure 5 presents the workflow of the AE simulation which also includes the workflow of simultaneous crack – wave propagation simulation.

Before presenting the results from the above simulation following similar approach a 100 mm x 100 mm x 2 mm thick plate was considered. To understand if a complicated problem could be solved using PED, the plate was reinforced with a stringer and wave behavior was successfully characterized with and without stringer. Figure 6 and 7 shows the wave field comparison in a 100 mm x 100 mm plate.

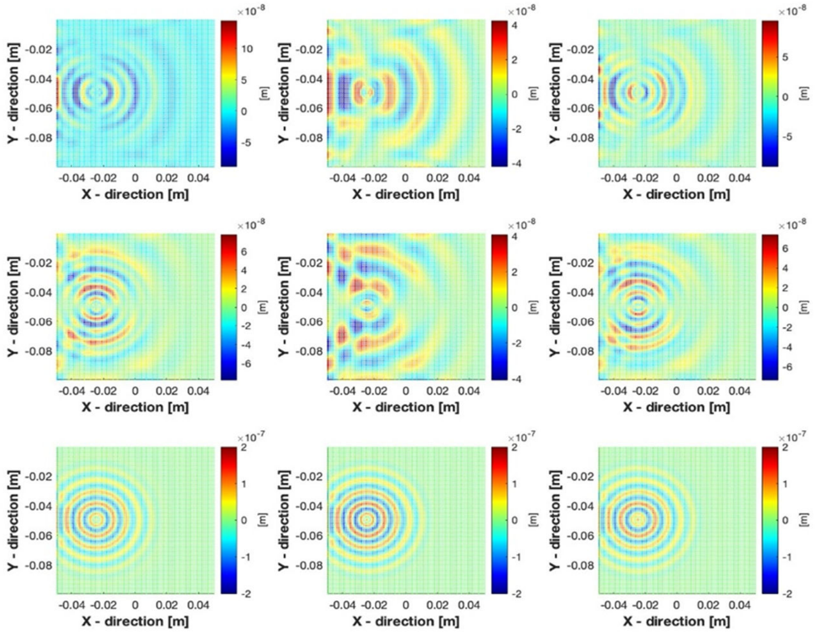


Figure 6: Wavefield computation using PED in a plate 100 mm x 100 mm x 2 mm thick. Wavefield on the: Top layer (top row), Middle layer (middle row), bottom layer (bottom row). Displacement: u_x displacement (first column), u_y (2nd column), u_z (3rd column).

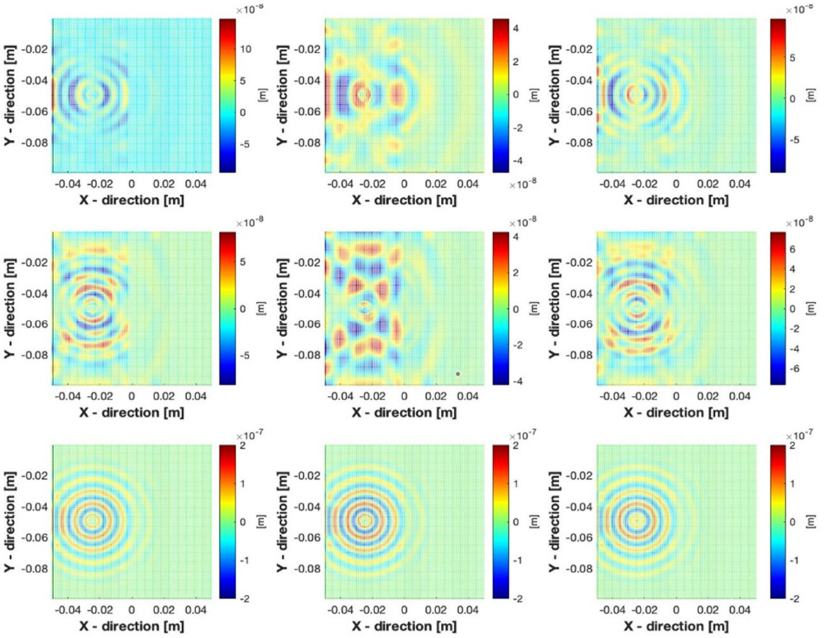
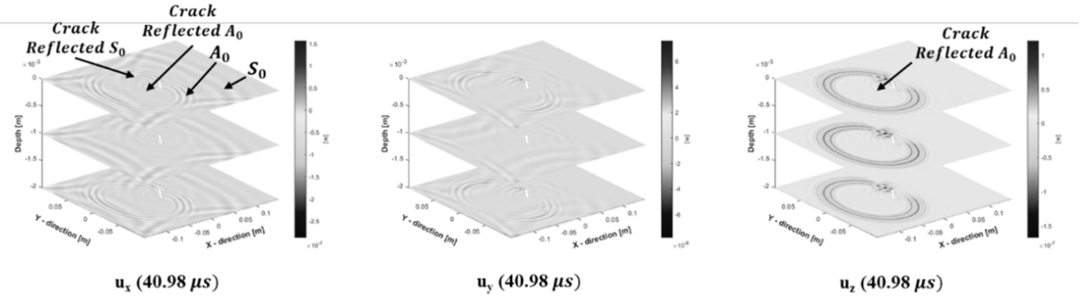


Figure 7: Wavefield computation using PED in a plate 100 mm x 100 mm x 2 mm thick with a 7.5 high stringer. Wavefield on the: Top layer (top row), Middle layer (middle row), bottom layer (bottom row). Displacement: u_x displacement (first column), u_y (2nd column), u_z (3rd column).

RESULTS AND DISCUSSION

As it is proved that complicated geometry could be handled by PED, it is further asked if PD approach can solve the physics for both crack propagation and wave propagation within one framework. Visualization of the interaction of wave with growing crack is quite challenging since the particle displacement would be a resultant of both wave and external loading. The particle displacement for wave amplitudes needs to be isolated and shown in Figure 8. As expected, both A0 and S0 mode are present on top and bottom layer for in plane $u_x \: and \: u_y$ motion. In similar manner, A0 mode is strongly present in all layers for out of plane, u_z motion. And the S0 mode is faintly present in top and bottom layer for u_z.



u_x (40.98 μs) u_y (40.98 μs) u_z (40.98 μs)

Figure 8 Time domain waveform for simultaneous crack – wave propagation

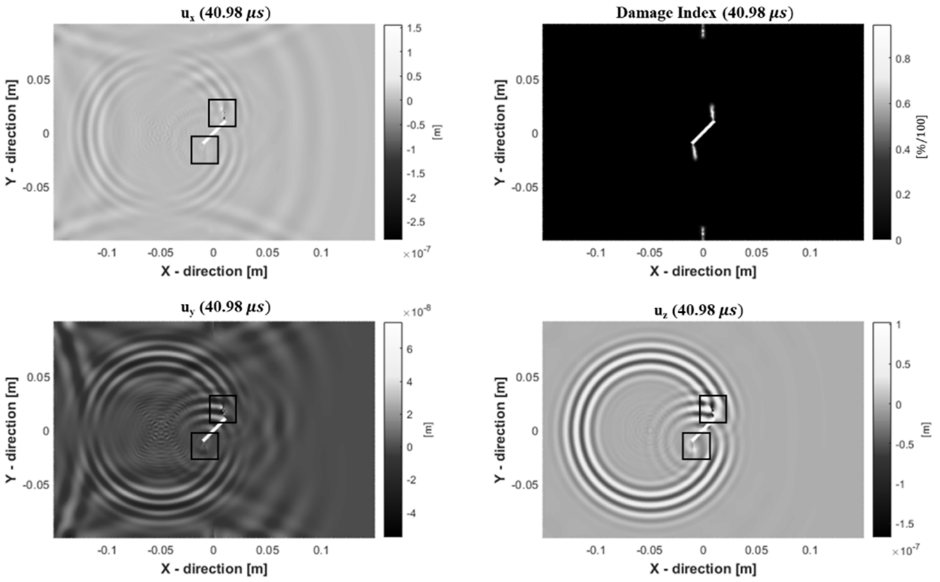


Figure 9 Time domain waveform at 40.98 µs on top layer compared with newly formed crack

Figure 9 presents a better understanding of the wave with the newly formed crack line. Displacement for every direction on top layer is shown with respect to Damage Index, which represents crack formation. Displacements near the crack line show irregular values instead of conforming with the circular crest of the wave. The antisymmetric wavefront is mostly affected by new crack formation because by the time crack started to propagate, the symmetric mode has already passed through the existing crack area. The reflected symmetric mode seen in this figure is the interaction between wave and existing crack.

CONCLUSION

The Multiphysics simulation of simultaneous crack propagation and guided wave propagation presented in this article provides a utilitarian way for the realization of Physics based deep link Digital Twin. The displacement boundary condition provides the service like condition where continuous external loading is present along with local sensors. This simultaneous continuous loading and guided wave from the sensors provide more information on the dynamic structural behavior during crack growth rather than using static loading. In future, this local monitoring of crack growth combined with global SHM data could be employed for the training of ML model for future damage prediction. Since service like condition is included in the dataset, the ML model would perform better to predict structure behavior in variable service conditions and accurately predict future lifespan. Separate AI/ML models can also be trained through this simulation technique by generating a multitude of data of variable environmental conditions which would be impossible to do in laboratory settings.

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