High-Fidelity Modeling for Health Monitoring in Honeycomb Sandwich Structures

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Abstract—High-Fidelity Model of the sandwich composite structure with real geometry is reported. The model includes two composite facesheets, honeycomb core, piezoelectric actuator/sensors, adhesive layers, and the impactor. The novel feature of the model is that it includes modeling of the impact and wave propagation in the structure before and after the impact. Results of modeling of the wave propagation, impact, and damage detection in sandwich honeycomb plates using piezoelectric actuator/sensor scheme are reported. The results of the simulations are compared with the experimental results. It is shown that the model is suitable for analysis of the physics of failure due to the impact and for testing structural health monitoring schemes based on guided wave propagation.

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1. Introduction

During a few past decades advanced composite materials such as sandwich structures have been steadily replacing traditional materials such as e.g. aluminium, steel, and solid fiberglass in many industries producing everything from storage containers to the key structural components of heavy lift space vehicles. The key advantages of sandwich structures include [1], [2] high stiffness to weight ratios, stability under compressive forces, improved fatigue life, and good thermal and acoustic isolation properties. These advantages determine the fact that the use of composites has increased significantly in a wide range of structural applications and first of all in aerospace industry. In the context of aerospace applications it is especially important to have fast and reliable on-board fault detection and prognostic system (FD&P) for structural health monitoring (SHM) of the sandwich composite materials.

There are numerous techniques currently under investigation [3] for diagnostics including for example: embedded fiber optic sensors for strain measurement, micro- electromechanical system accelerometers for vibration measurement, active ultrasonics, passive acoustic emission monitoring, and electromechanical impedance measurements. One of the most promising SHM techniques is Lamb wave based diagnostics of composite plates [4]. Lamb waves are of particular interest due to the similarity between their wavelength and the thickness of composite structures generally used, the ability to travel far distances, high sensitivity, active sensing and low cost of piezoelectric wafer actuators/sensors.

However, there are several fundamental issues related to this technique including understanding the wave propagation mechanism in the honeycomb composites, analyzing measured responses due to the multimodal and dispersive characteristics of Lamb waves, and understanding of the physical mechanisms underlying damage initiation, propagation and interaction with the Lamb waves. It is very desirable therefore to develop alternative methods of the analysis and simulations of the sandwich panels that can shead new light onto the physics of wave propagation and damage mechanisms. A very promising approach to this problem is based on the commercially available finite element (FE) code [5]. The earlier results are especially promising because sandwich structure with honeycomb core (SSHC) is one of the primary candidates in the aerospace applications.

In the present paper we extend the technique by including impact into the modeling scheme and analyzing detection of the impact-induced damage by piezoelectric actuator/sensor pairs. Such an extension is important in a view of SHM applications especially taking into account the fact that failure modes [6], [7] of the SSHC under concentrated dynamical impacts depend on the structural details. In other words such an extension will also provide further insight into the physics of failure of SSHC. The results of the numerical simulations are validated by comparison with the experimental results performed by Metis Design Corp. (MDC).

The paper is organized as follows. The details of the finite element model build in Abaqus to simulate wave propagation, impact and scattering by the damaged area are discussed in the Sec. 2. The experimental setup and geometry of the actuator sensors placement is briefly outlined in Sec. 3. The comparison of the numerical results of the wave propagation with the experimental results is given in Sec. 4. The details of the impact modeling and a comparison of the honeycomb core crash induced by the impact in the simulations and an experiments are given in Sec. 5. The results of modeling of the surface wave scattering by the damaged area in comparison with the experimental results are discussed in Sec. 6. The obtained results are summarized and discussed in the Sec. 7.

2. Finite Element Model

The model of the honeycomb sandwich structures with a piezoelectric actuator/sensor distribution is shown in the Figure 1. The model consists of the honeycomb core and two laminated facesheets with actuator and sensors attached to the top sheet. The facesheet in Abaqus were modeled using continuum shell element type with the composite layup parameters shown in the Table 1

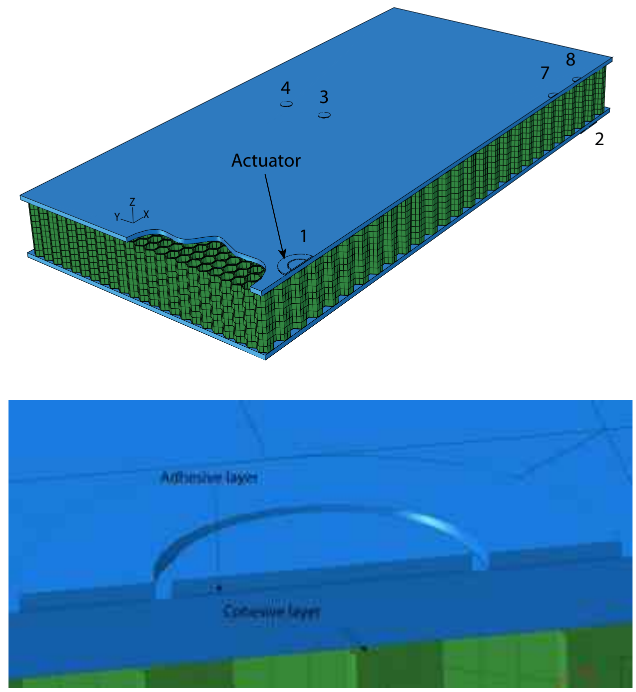


Figure 1. (top) Finite element model of the sandwich honeycomb structure with a piezoelectric actuator (shown by an arrow) and a set of sensors (marked by the numbers). (bottom) A magnified view of the actuator and sensor attachment to the facesheet surface. The important adhesive layer placed between sensor/actuator and the facesheet can also be seen in the figure. The geometry of sensor/actuator placement is the same as in the experiment as shown in the Fig. 2.

Table 1. Parameters of the facesheet

Parameter	**Value**
Ply elastic modulus E_{11}	16 Msi
Ply elastic modulus E_{22}	1.2 Msi
Ply Poisson's ratio ν_{12}	0.3
Ply shear modulus G_{12}	0.6 Msi
Ply thickness	6 mils
Laminate thickness	84 mils

The type A analog Monitoring & Evaluation Technology Integration (METI) -disks have an actuator and sensor in the form of a concentrically placed lead zirconium titanate (PZT)-5A washer and disc respectively (actuator and sensors 1 and 2 in the Fig. 1). The actuator ring has nominal outer and inner diameters of 1.80086 cm and 1.00076 cm respectively, while the "type A" sensor has a nominal diameter of 0.89916 cm. Both have a nominal thickness of 20 mils. The "type B" METI-disk has a sensor disk of nominal diameter 0.635 cm and nominal thickness of 10.5 mils. The response of the PZT elements was determined by the piezoelectric stress matrix e

and elasticity matrix c

$$[e] = \begin{bmatrix} 0 & 0 & -5.4 \\ 0 & 0 & -5.4 \\ 0 & 0 & 15.8 \\ 0 & 0 & 0.0 \\ 0 & 12.3 & 0.0 \\ 12.3 & 0 & 0.0 \end{bmatrix} [Cm^{-2}] \tag{1}$$

$$[c] = \begin{bmatrix} 12.1 & 7.54 & 7.52 & 0 & 0 & 0 \\ 7.54 & 12.1 & 7.52 & 0 & 0 & 0 \\ 7.52 & 7.52 & 11.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.26 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.11 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.11 \end{bmatrix} \times 10^{10} [Pa] \tag{2}$$

The dielectric matrix of the PZT material has the following diagonal elements $\varepsilon_{11} = \varepsilon_{22} = 8.11 \times 10^{-9}$ [C/V/m] and $\varepsilon_{33} = 7.35 \times 10^{-9}$ [C/V/m]. The density of the PZT material is $\rho_{PZT} = 7750$ [kg/m^3]. The geometry of sensor/actuator placement is the same as in the experiment as shown in the Figure 2.

A special attention was paid to modeling detailed honeycomb structure including the difference in thickness for different walls of the structure and the presence of the bending tips. The structure was built from a single strip using patterning operation in Abaqus. The bending tips were attached to the structure using boolean operation on the mesh. The height of the core cell is 2.54 cm and the size of the cell is 0.635 cm. The material properties of the Aluminum used to build the structure are the following: Young's modulus $E_{Alm} = 7.3084 \times 10^{10}$ [Pa], Poisson's ratio $\nu_{Alm} = 0.33$, Mass density $\rho_{Alm} = 2700$ [kg/m^3].

Important property of the honeycomb sandwich structure is the presence of adhesive layers both between actuator/sensors and facesheet and between facesheet and honeycomb core. The role of the adhesive layer between PZT elements and the composite facesheet was emphasized earlier in [8]. Accordingly the layer with the following properties (Young's modulus $E_{Adh} = 4.82 \times 10^9$ [Pa], Poisson ratio $\nu_{Adh} = 0.40$, and mass density $\rho_{Adh} = 1255$ [kg/m^3]) was explicitly included into the finite element model as shown in the Figure 1.

For impact modeling the cohesive elements for the adhesive layer between facesheet and the honeycomb core is essential part of the model.

3. Experimental setup

In order to evaluate the applicability of the structural health monitoring methodology, i.e. Lamb-wave method for honeycomb sandwich structures of interest to NASA, some preliminary experiments were done at Metis Design Corporation. A representative honeycomb-sandwich panel was fabricated for this test. It consists of two 84-mil thick cross-ply carbon fiber composite laminates bonded to a 2.54cm-thick aluminum honeycomb core. The experimental setup is shown in the Figure 2. This panel was instrumented with a network of analog METI-disk nodes. These sensor nodes can be used for both modal testing and Lamb-wave methods. A schematic diagram of the panel with METI-disk locations and numbering scheme are shown in Figure 2.

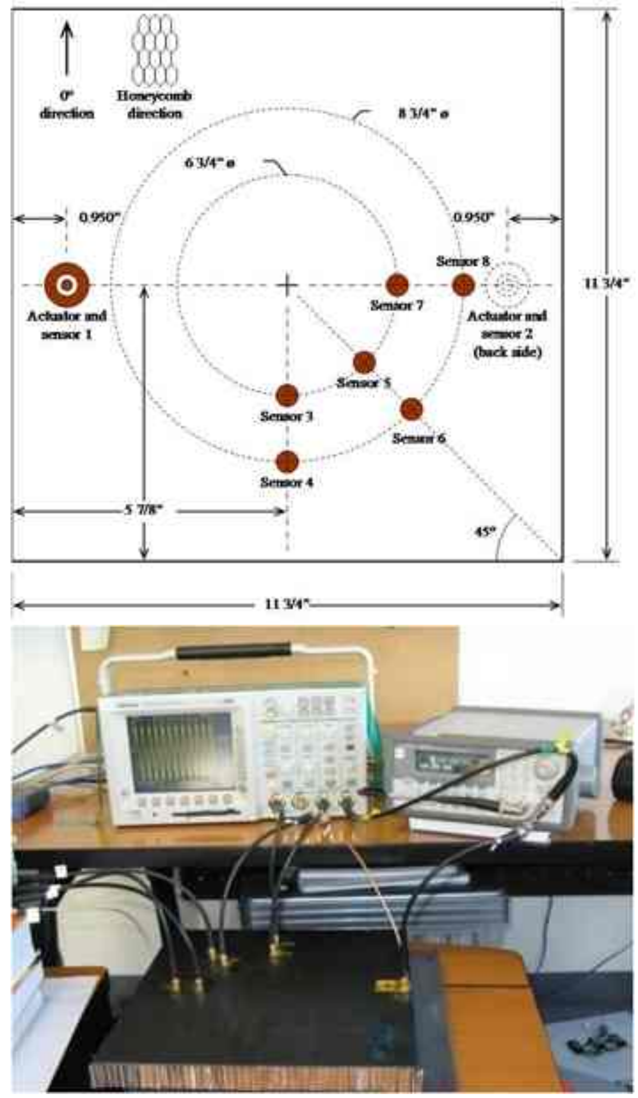


Figure 2. (top) The experimental setup with PZT patches bonded to the surface of the SSHC. (bottom) Photograph of the experimental setup.

4. Modeling wave propagation

To excite Lamb wave in the model the voltage boundary conditions were applied to the top of the actuator. The amplitude of the applied voltage was varied according to the table data. The simulations were performed in a frequency range from 20 to 125 kHz. A 3.5-cycle Hanning windowed toneburst was used as actuation signal at each frequency. The shape of the driving signal $V_{dr}(t)$ both in the experiment and

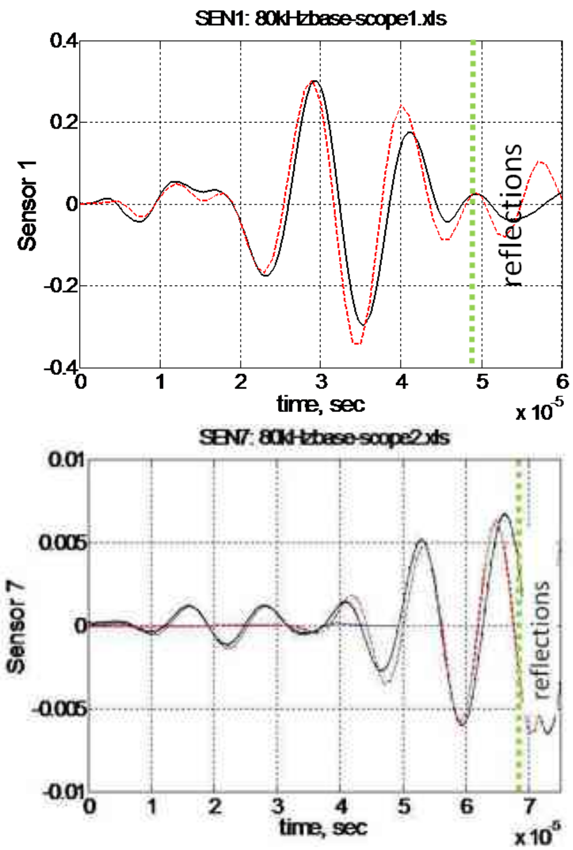


Figure 3. The results of the simulations of the wave propagation in honeycomb structure are shown in comparison with the experimental results measured for 80 kHz on (a) sensor # 1 embedded into actuator and (b) sensor # 7.

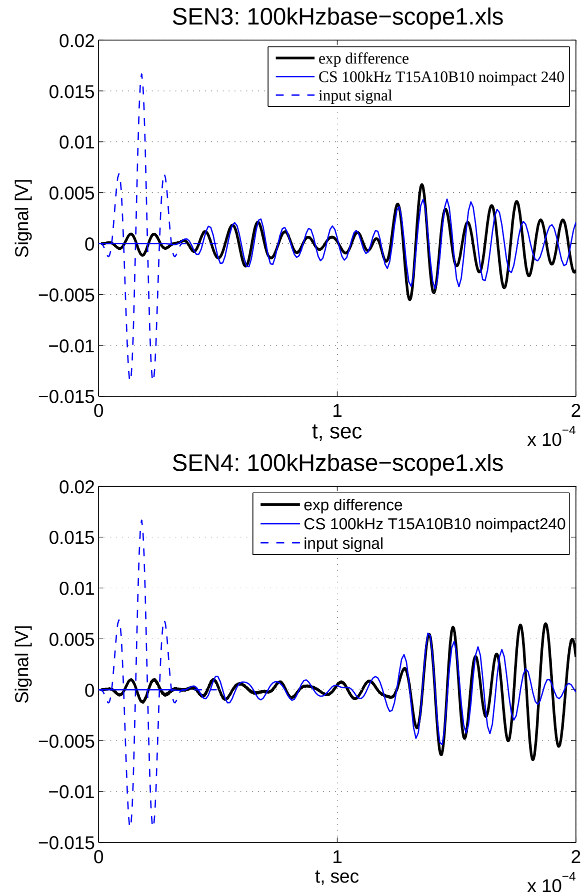


Figure 4. The results of the simulations (blue lines with open circles) of the wave propagation in honeycomb structure are shown in comparison with the experimental results (black solid lines) measured for 100 kHz on (a) sensor # 3 and (b) sensor # 4. The driving signal is shown by dashed blue lines with scale.

simulations was

$$V_{dr} = V_0 \sin(2\pi f_{dr} t) \cdot (\sin(\pi f_{dr} t / N_{waves}))^2, \qquad (3)$$

where V_0 and f_{dr} are the amplitude and the frequency of the driving voltage, and the number of waves N_{waves} was set to 3.5. Some of the results of the simulations are shown in the Figures 3 and 4 in comparison with the experimental results.

A good agreement between the numerical and experimental results was obtained for a few first cycles of incoming signal. The difficulties in reproducing experimental results over the whole time-span of the experimental signal are related to the three main factors. Firstly, the boundary conditions for the honeycomb structure in the experiment were not well defined. The uneven shape of the boundary can be seen at the photograph of the experimental setup Figure 2 (bottom). Secondly, the actuators and sensors were placed very close to the boundaries of the plate, which was only 11 inch wide. Thirdly, the adhesive layer at the plate edges was affected by cutting.

Furthermore, in the context of aerospace applications a thick panels (with approximately 2.54 cm thickness) are of special interest. The spectrum of guided waves in such panels is morel complicated (see e.g. [9]). The later fact introduces additional difficulties in modeling such structures. As a result of these difficulties a careful optimization of the model parameters is required to achieve a better agreement with the experiment. Extensive parametric studies of the finite element model revealed the sensitivity of the model to the coupling between the PZT and facesheet and between the facesheet and honeycomb core.

After optimization the agreement between the experimental and numerical results was further improved mostly for two sensors (# 3 and # 4) which are most distant from the boundaries. The corresponding results are shown in the Figure 4. It can be seen from the figure that simulations can capture accurately the propagation of the lowest symmetric (S_0) and antisymmetric (A_0) modes of the system.

5. Impact

A very promising results of the simulations of the wave propagation in the sandwich composite structure described in the previous section prompt us to seek further extension of the

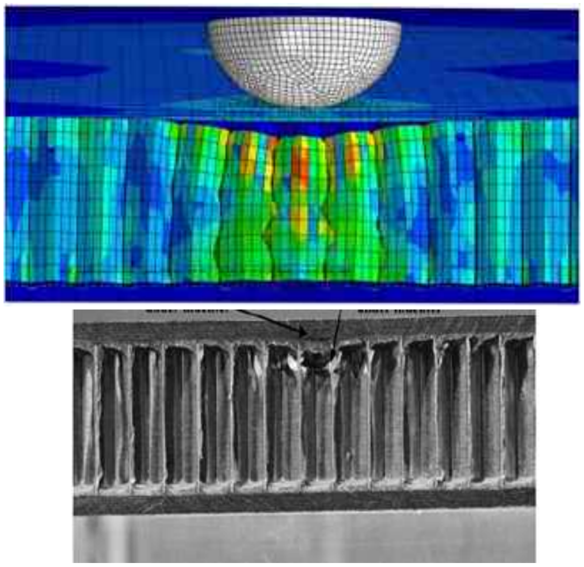


Figure 5. (a) Results of the simulation of the impact showing crashed honeycomb core. (b) Experimental results demonstrating crushed honeycomb structure due to impact.

model capabilities by including first of all the impact into the modeling scheme. To model impact a finite element model of the impactor was introduced in Abaqus both as a solid body model and as an analytical rigid body. The impactor mass was fixed and the velocities of the impact were calibrated in the range 20 to 240 lib-inch to reproduce the experimental setup.

In the experiment performed by Metis Design Corp. the panel was impacted using the calibrated impactor. The diameter of the semi-spherical impactor head is 1.27 cm. The panel was subject to controlled impacts of increasing energy (10, 20, 30, 60 and 120 inch-lbs) and data was collected after each impact. The panel was impacted at the center of the upper face sheet (which has all METI-disks bonded to it except the A2/S2 pair). These impact energy levels were chosen based on earlier calibration tests using another honeycomb panel to introduce hidden delaminations at the lower energy levels, barely visible damage at the intermediate levels, all the way up to visible damage at the higher energy levels.

The facesheet was not visibly damaged in these tests and the modeling efforts were focused on the analysis of the honeycomb crush. The cohesive elements were introduced between the facesheet and the honeycomb core to allow for the core crush in explicit dynamic simulations. The quadratic nominal stress damage criterion was used for cohesive elements where the cohesive layers are defined in terms of traction-separation. The PZT actuators and sensors had to be removed from the model in these simulations.

The results of the simulation of the impact are shown in the Figure 5 in comparison with the experimental results [10]. It can be seen from the figure that the results of simulations can reproduce qualitatively well the honeycomb crush observed in the experiments. we note that the main effect of the impact is the damage of the honeycomb core. The damage can be characterized by the radius of the debond and the maximum depth of the debond. For example for the results of simulations shown in the Figure 5 the maximum depth of the debond is approximately 0.2 cm while the diameter of the debond is of the order of 3.4 cm for the impact strength 240 lib-inch. Both parameters are very sensitive to the properties of the cohesive layer and the damping of the honeycomb material. The optimization of the impact model parameters using experimental results is currently under way.

6. Modeling damage detection

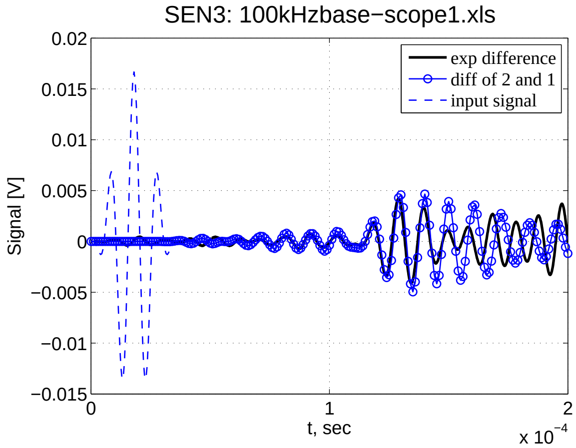
To model wave propagation in the impacted panel the honeycomb core in the original model (see Figure 1) was substituted with the core obtained in impact simulations. The simulation of the wave propagation were repeated under conditions described in Sec. 4. The signal scattered by the damaged area was extracted as a difference between signals obtained in simulations with and without impact. Similar procedure was applied to extract scattered signal from experimental data.

We emphasize that in simulations of the guided wave propagation both before and after the impact the response of the system was measured as an integrated voltage on the top surfaces of the PZT sensors. No scaling factor was involved into the conversion.

The comparison of the scattered signals obtained in the simulations and in the experiment is shown in the Figure 6 for impact strength 240 lib-inch. The best agreement was obtained for the sensors # 3 and # 4 because their measurements were least destructed by the reflections from the boundaries as was discussed earlier. It can be seen from the figures that scattering of the main wave components S_0 and A_0 can be accurately reproduced in simulations. The simulations also reveal direct proportionality between the amplitude of the scattered signal and the strength of the impact. The simulations also reveal that the flexural waves are more sensitive to the particular damage type analyzed in the present simulations.

7. Conclusions

In this paper we have reported a work in progress on developing a finite element model of the sandwich composite structure for an assessment of the on-board structural health monitoring of composite panels in aerospace applications. The characteristic features of the presented model include realistic geometry of the sandwich panel with thick and soft aluminium honeycomb core, the PZT actuators and sensors attached to the top and bottom faces of the panel, and the presence of adhesive layers between the facesheets and the core and between the PZT elements and the facesheets. The novel feature of the presented results is the explicit simulations of the impact and the comparison of the guided wave



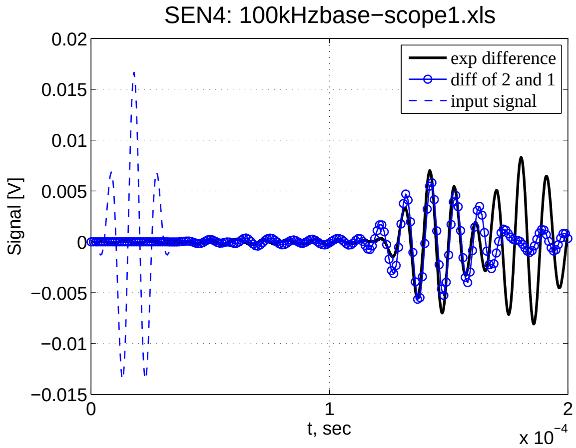


Figure 6. The results of the simulations (blue lines with open circles) of the damage detection by measuring the scattered signal as a difference between base signal and signal propagating in a damaged by impact honeycomb structure are shown in comparison with the experimental results (black solid lines) measured for 100 kHz on (a) sensor # 3 and (b) sensor # 4. The driving signal is shown by dashed blue lines with scale.

propagation in the panel before and after impact.

The simulations were verified by comparison with the experimental results performed by Metis Design Corp. The obtained numerical results demonstrate good agreement with the experimental results of the wave propagation in sandwich structure. The agreement is improved if the influence of the reflection from uneven boundaries is reduced for two particular sensors # 3 and # 4. The results of the impact simulations reveal the dynamics of crushing of the honeycomb core. The obtained in simulations damage of the core is in qualitative agreement with the experimental results. The simulations of the guided wave propagation in the panel with crushed honeycomb core also demonstrate a good quantitative agreement with the experimental results. The simulations show that the amplitude of the scattered signal is proportional to the impact strength and that the flexural waves are more sensitive to the particular type of the defect investigated in the present research as compared to the symmetric Lamb waves.

The obtained results are promising and confirm that pulse-echo and pitch-catch technique of damage detection is a good candidate for on-board structural health monitoring of the composite structures in aerospace applications.

Further work is required to continue extensive sensitivity analysis of the finite element model and its validation using experimental results. The corresponding efforts are currently under way and experiments with larger composite panels with reduced effect of boundary reflections are under preparation. In addition an extensive analytical research is curried out that captures the main features of the guided wave propagation in the sandwich panels, models the impact-induced damage, and scattering of the Lamb waves in the impacted panels in the Mindlin approximation. A preliminary comparison between the analytical and numerical results is also promising and confirms the main conclusions drawn in the present research.

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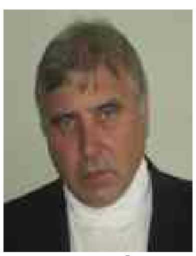

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