

# Strain Wave Analysis in Carbon-Fiber-Reinforced Composites subjected to Drop Weight Impact Test using ANSYS®

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## **ABSTRACT**

Composite materials are becoming more popular in technological applications due to the significant weight savings and strength these materials offer compared to metallic materials. In many of these practical situations, the structures suffer from drop impact loads. Materials and structures significantly change their behavior when submitted to impact loading conditions as compared to quasi-static loading. The present work is devoted to investigating the elastic strain wave in Carbon-Fiber-Reinforced Polymers (CFRP) when subjected to a drop test. A novel drop weight impact test experimental method evaluates parameters specific to 3D composite materials during the study. A strain gauge rosette is employed to record the kinematic on the composites' surface. Experimental results were validated through numerical analysis by FDM Numerical Simulations in MATLAB® and ANSYS® Explicit Dynamic Module. A MATLAB® code was developed to solve wave equation in a 2-D polar coordinate system by discretizing through a Forward-Time Central-Space (FTCS) Finite Difference Method (FDM). Another FEA analysis was performed in ANSYS® Workbench Explicit Dynamics module to simulate the elastic waves produced during the DWIT. The study demonstrates that the elastic waves generated upon impact with a 33 g steel ball from a height of 1 m in a quasi-isotropic CFRP sheet give a strain wave frequency of 205 Hz and finish in almost 0.015 s due to a significant damping effect. Numerical simulations were in good agreement with the experimental findings.

## **1. INTRODUCTION**

Materials are the fundamental elements of all-natural and man-made structures. Usually, new materials emerge due to the necessity to improve structural efficiency and performance. One of the best manifestations of this interrelated process is associated with composite materials.

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Composites, which consist of two or more different materials combined in a structural unit, are typically made from various combinations of the materials. Composites are generally used because they have the required properties that cannot be achieved by any constituent materials acting alone. The most common example is the fibrous composite consisting of reinforcing fibers embedded in a binder or matrix material. In general, fibers are the principal load-bearing members, while the surrounding matrix keeps them in their allocated position, and orientation acts as a load transfer medium between them and protects them from environmental damages due to chemical corrosion and humidity [1-4]. Carbon fibers reinforced polymers offer a combination of strength and modulus comparable to or better than many traditional metallic materials. Despite many superior properties of composites over metals, they are susceptible to damages caused by low-velocity impact during service, reducing their performance to a great extent [5-8].

### 1.1. Drop Weight Impact Testing (DWIT)

Various previous works have mentioned the importance of each of these concepts separately [1-8], but recent researches demonstrate that both concepts should be taken simultaneously into account to improve characteristics and security level of structural systems [9-13]. So, it is very important to determinate how to use the reliability and vulnerability analyses for making decisions on critical infrastructures or structures. The reliability can be defined as the probability that the system or more of its elements functions (it is the ability of the studied system to ensure the desired operations in continuity). Vulnerability, on the other hand, can be defined as the likely damage of a failure event (it is the level of the system degradation under random failures effects, which make the system out of service).

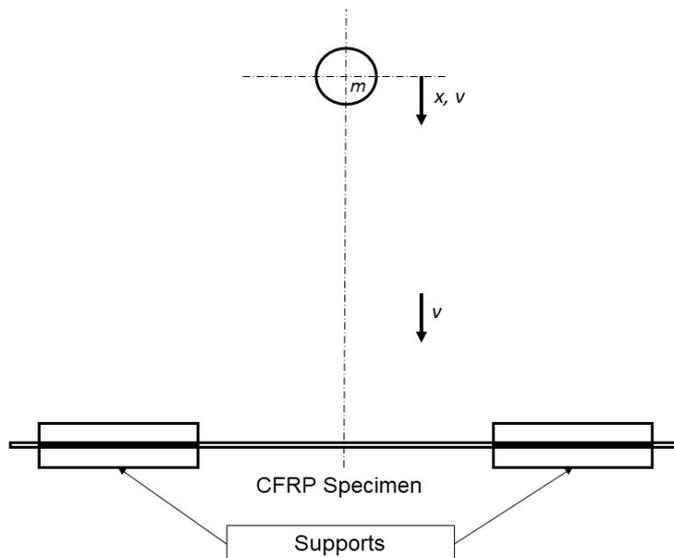


Figure 1: The Drop Weight Impact Test method.

## 1.2. Numerical Analysis

Different modeling techniques are used to model the impact dynamics of composite structures [10]–[13]. In general, there are four categories considered: energy-balance models, which assume a quasi-static condition; spring-mass models that simplify the dynamics of the structure; complete models in which the full behavior of the structure is modeled; and finally, a model for impact on infinite/ finite plates. The infinite plate model can be considered if the deformation wave front doesn't reach the boundary of the plate; if the wave propagation reflects on the plate boundaries back to the point of impact, then the finite size of the test sample must be considered [14].

## 1.3. Methodology

In this research, the elastic waves response of Carbon Fiber Reinforced Polymers (CFRP) subjected to high strain rates are to be investigated by means of a novel DWIT experimental setup. Fiber-reinforced composites are usually manufactured by stacking laminae of sheets of fibers pre-impregnated with resin. Therefore, the structure is heterogeneous, so consideration should be made of the stress discontinuities between the fibers and matrix [15,16]. This study aims to investigate the strain waves produced on surface of CFRP material when it is impacted.

The study was divided into two phases. The first phase was the experimental study that involved performing DWIT with specialized rosette strain gauge, amplifiers, and a high-speed oscilloscope. This study yielded useful insight into the oscillatory elastic deformation within CFRP when subjected to drop weight impacts.

The second phase constituted the development of Numerical Models to describe the physical problem that is predicted from the experimental findings. During the first half of this study, the Wave Equation in polar coordinate systems is solved using the Forward-Time Central-Space (FTCS) Finite Difference Method (FDM) method using MATLAB® software [17]. During the second half commercially available ANSYS® Explicit Dynamic Module was used to perform the FEA study. The derived Numerical Analysis solutions were validated from experimental findings to optimize the models.

## 1.4. CFRP Sample

Test samples used in this study were from the DragonPlate®, manufactured by Allred and Associates Inc., Elbridge, New York [18]. The sample was a solid quasi-isotropic carbon fiber sheet of thickness 1 mm, as shown in Figure 2 [19]. CFRP sheets comprised of five plies at  $0^{\circ}/+45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}$  orientation laminates (Figure 2). The sample was composed of a tough and rigid carbon reinforced epoxy matrix, with a textured finish on both sides. The properties of the samples are given in Table 1.

Table 1: Properties of CFRP samples [18]

Carbon Fiber Modulus	228 GPa
Weight of sheet	72.1 g
Density	1540kg/m <sup>3</sup>

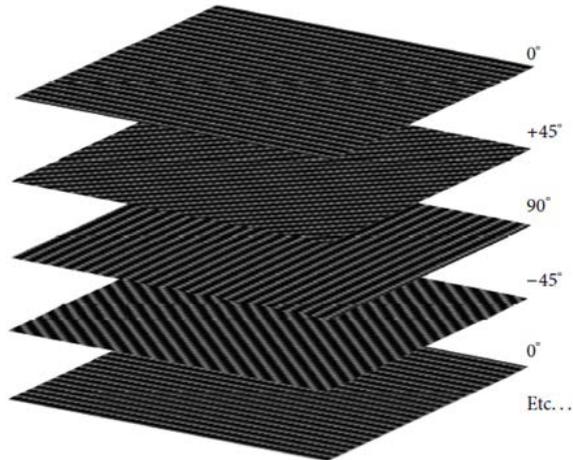


Figure 2: Carbon Fiber Quasi-Isotropic Sheets [176].

## 2. EXPERIMENTAL SETUP TO PERFORM A DROP TEST

Drop Weight Impact Test Experiment was performed using a spherical steel ball of 20mm diameter, as shown in Figure 3 [20,21]. A rosette strain gauge stacked configuration (at 0°, 45°, and 90°-degree direction) is attached at the bottom of the CFRP plate (backside of the plate), as shown in Figure 4. Acquisition of differential strain vector from baseline was achieved using op-amp circuit and high-speed oscilloscope at 100 MHz sampling frequency rate. The CFRP plate is clamped in a circular flange to prevent the plate from moving during the DWIT, as shown in Figure 5 and Figure 6. The diagrammatic representation of the experiment is shown in Figure 7.



Figure 3: Steel ball (spherical) of 20 mm diameter and 33g weight.



Figure 4: Rosette strain gauge attached at the back of the CFRP sample.



Figure 5: CFRP sample clamped in a circular flange of inner diameter 173 mm (top view).



Figure 6: CFRP sample clamped in a circular flange (side view).

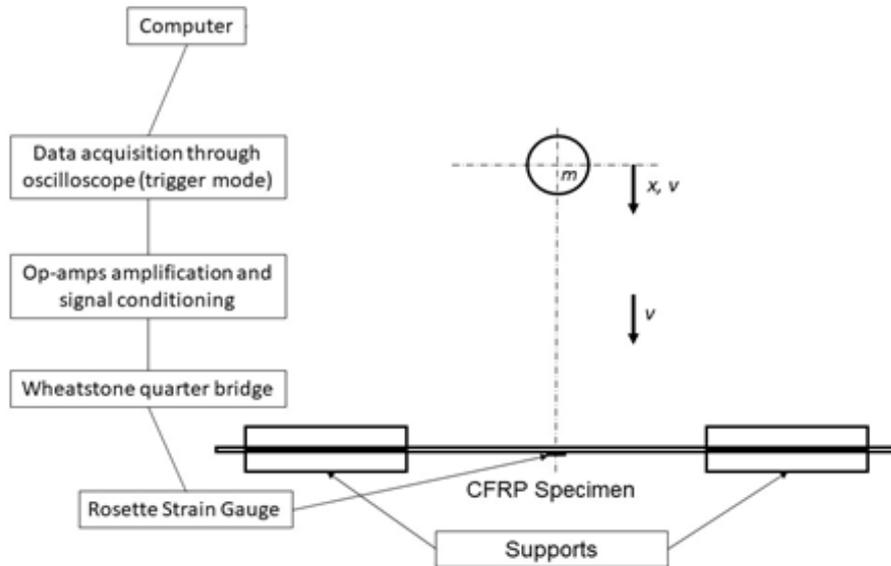


Figure 7: Diagrammatic representation of the experiment.

### 3. NUMERICAL ANALYSIS

#### 3.1. Finite Difference Method (MATLAB®)

The Finite Difference Method (FDM) is a numerical method for solving differential equations such as the two-dimensional wave [22-27], as given in Equation 1. This method approximates the differentials by discretizing the dependent variables (strain) in the independent variable domains (space and time, in this case) [27-29]. Each discretized value of the dependent variable is referred to as a nodal value. In this case, 2D wave equations in the cylindrical coordinate system are discretized using a Forward-Time Central-Space (FTCS) FDM. The discretized equations are given as Equation 3. The two-dimensional wave equation in the cylindrical coordinate system is shown in Equation 1:

$$\frac{1}{c^2} \left( \frac{\partial^2 u}{\partial t^2} \right) = \frac{1}{r} \left( \frac{\partial u}{\partial r} \right) + \left( \frac{\partial^2 u}{\partial r^2} \right) + \frac{1}{r^2} \left( \frac{\partial^2 u}{\partial \theta^2} \right) \quad (1)$$

where  $u$  is the strain,  $r$  is the radius,  $\theta$  is the angle in degrees, and  $c$  is the speed of a sound in a medium as shown in Equation 2:

$$c = \text{frequency} * \text{wavelength} \quad (2)$$

$$\frac{1}{c^2} \left( \frac{u_{i,j}^{t-1} - 2u_{i,j}^t + u_{i,j}^{t+1}}{(\Delta t)^2} \right) = \frac{1}{r} \left( \frac{u_{i+1,j}^t - u_{i-1,j}^t}{2\Delta r} \right) + \left( \frac{u_{i-1,j}^t - 2u_{i,j}^t + u_{i+1,j}^t}{(\Delta r)^2} \right) + \frac{1}{r^2} \left( \frac{u_{i,j-1}^t - 2u_{i,j}^t + u_{i,j+1}^t}{(\Delta \theta)^2} \right) \quad (3)$$

### 3.2. FEA (ANSYS® Explicit Dynamic)

The second part of numerical analyses were performed in ANSYS® Workbench Explicit Dynamics [31] module to simulate the elastic waves produced during the DWIT upon impact, similar studies were performed [32-34]. The material for the impactor ball was chosen to be steel from the ANSYS® material library. The material assigned to the CFRP sample was the Epoxy Carbon unidirectional (230 GPa). The quarter geometric model is seen in Figure 8. Symmetry was used on the model in the negative z-direction and positive y-direction (as seen in Figure 9 and Figure 10) to ease the computational load of the simulation. The CFRP test piece and steel ball dimensions were the same as in the experimental test as shown in Figure 11.

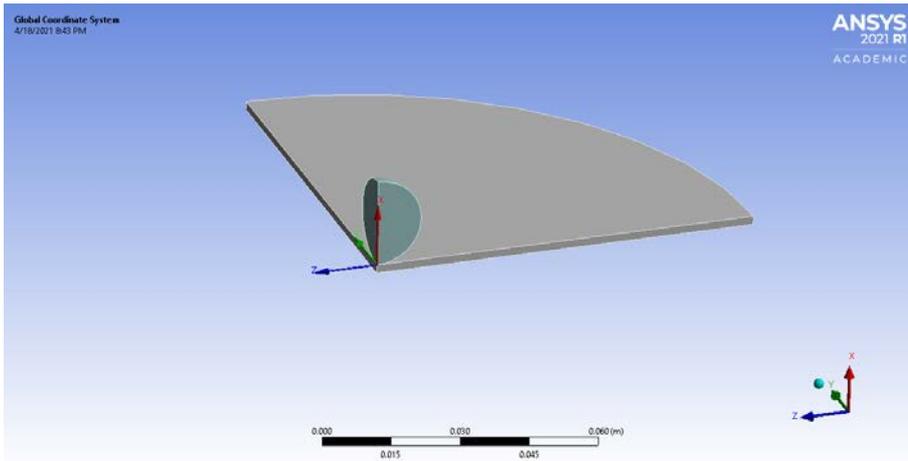


Figure 8: Quarter geometric model.

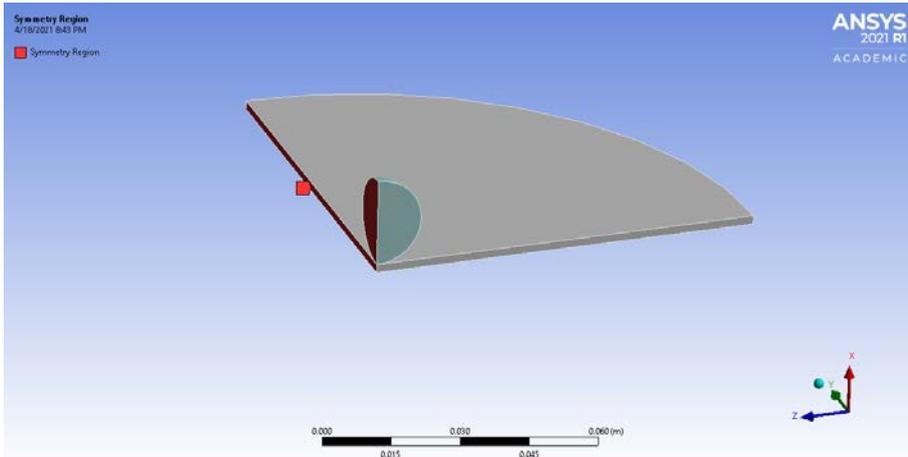


Figure 9: Symmetry applied in positive y-direction.

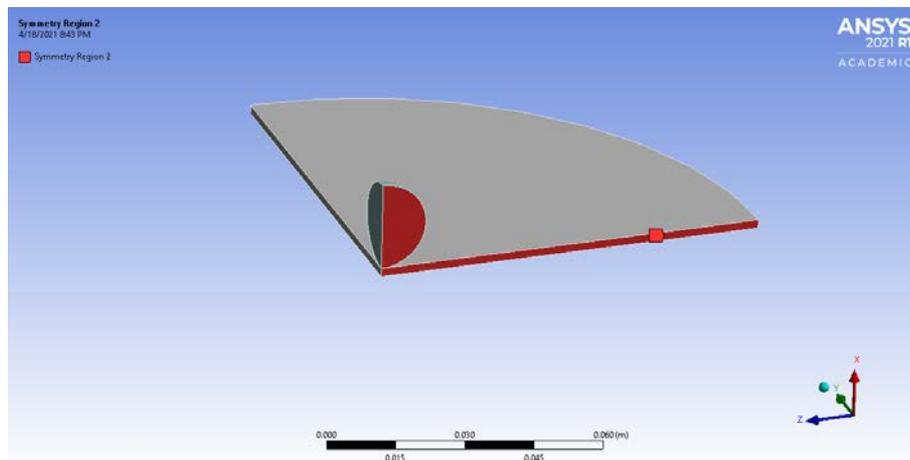


Figure 10: Symmetry applied in negative z-direction.

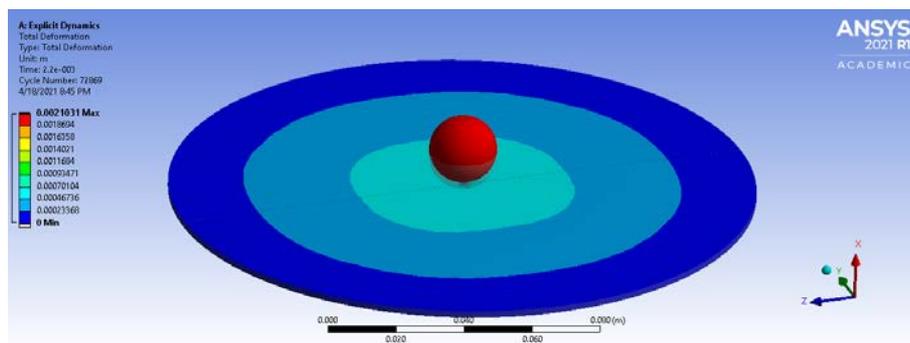


Figure 11: Full model of Steel impactor and CFRP test piece.

To create a finite element (FE) model, an automated mesh was generated in ANSYS® Workbench. The meshing of the model was limited by the number of elements/nodes allowed in the Academic license of ANSYS® Structural physics, which is 32000 nodes/elements. A mesh sensitivity analysis was performed by increasing the number of nodes and elements to see when the solution to the simulation converged. Mesh convergence was attained at a total node of 4348 and elements 16408. Figure 12 shows the Finite Element mesh generated in ANSYS® Workbench.

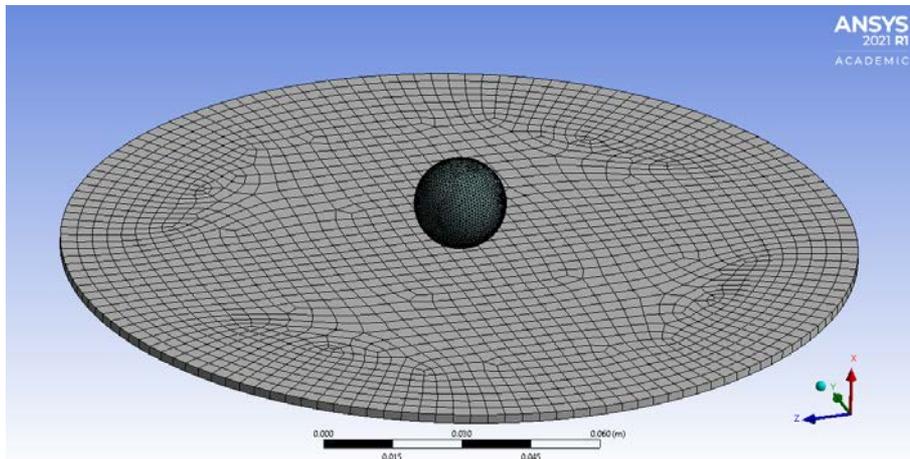


Figure 12: Finite element mesh.

Initial velocity assigned to the steel ball before impact was 4.43m/s in ANSYS® simulation, as shown in Figure 13. The surface that determines the thickness of the CFRP sheet was fixed, shown in Figure 14, as per the experimental setup.

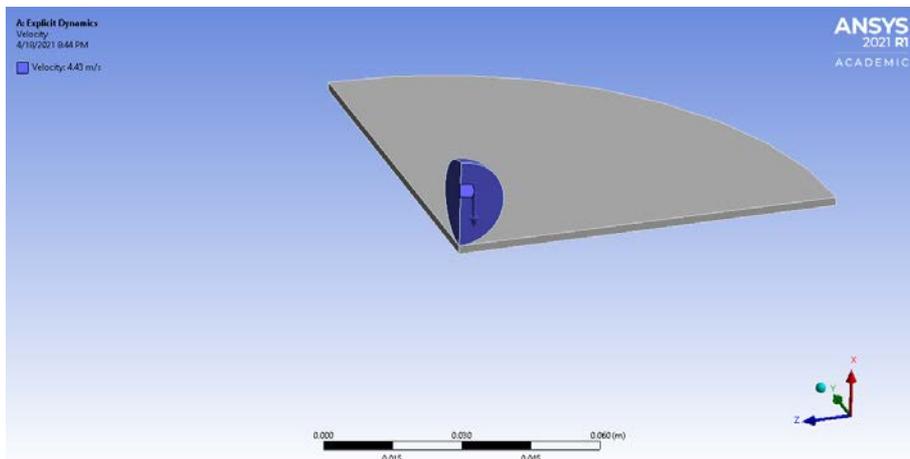


Figure 13: Initial velocity (4.43 m/s) specified to the steel ball.

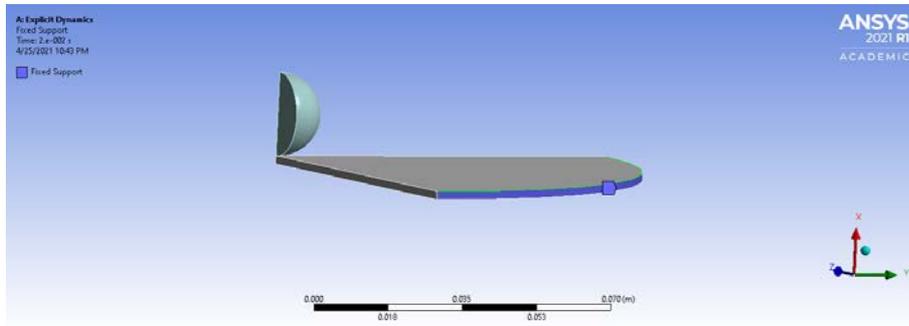


Figure 14: Fixed support surface.

The body interactions were assigned frictional contacts [35] as shown in Figure 15, with static and dynamic coefficient of friction values of 0.33.

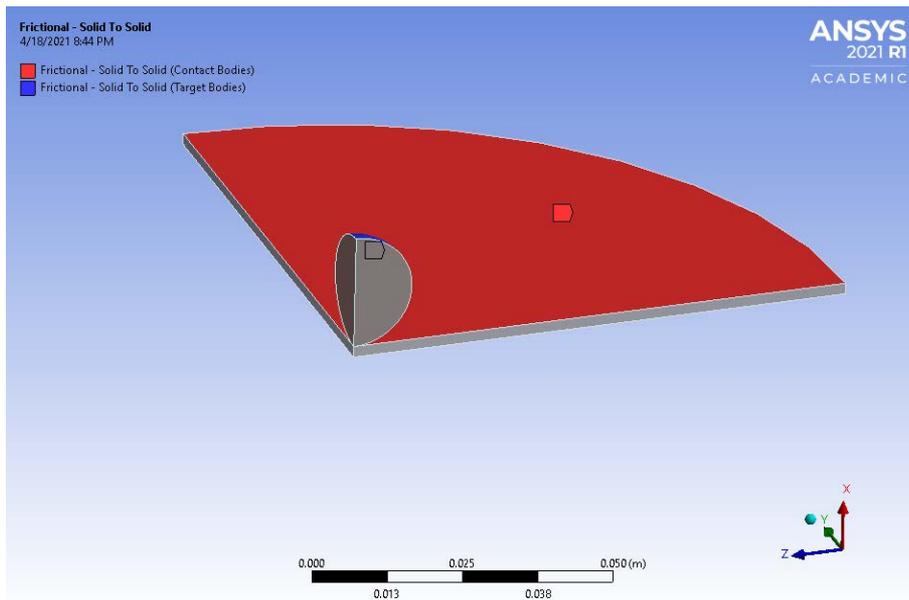


Figure 15: Frictional solid-to-solid contact.

#### 4. RESULTS AND DISCUSSION

Experiment strain data of a fully clamped CFRP plate (with 21000 times amplification using op-amp circuit and high-speed oscilloscope) at 100 MHz sampling frequency rate after signal processing give a strain wave frequency of 205 Hz. At the time of impact, the highest value of strain recorded is 2.5 micro strain, but this value is due to the ball's momentum and not representative of the natural response of the CFRP plate. After the ball is removed, the plate vibrates naturally, and the value of 0.5 micro strain is recorded, as shown in Figure 16. This value is used to solve wave equation by the FDM method in MATLAB®. It is also observed that the strain waves undergo significant damping, and amplitude drops to 0.15 in 0.012 s. Dynamic strain reflects the behavior of CFRP under drop impact for in-plane measurement.

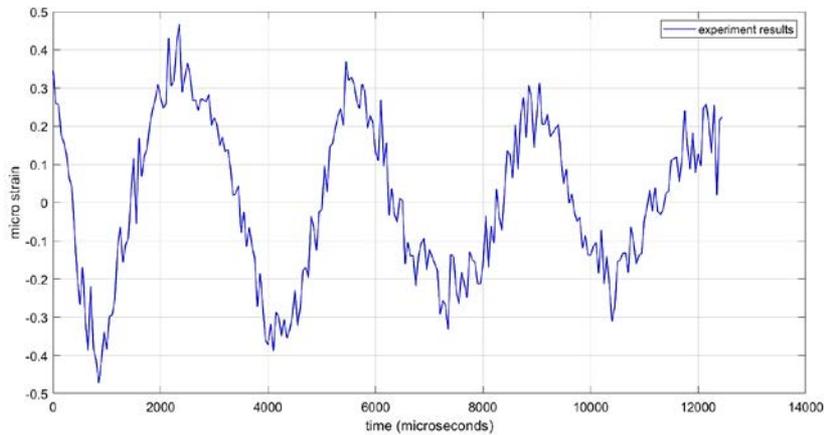


Figure 16: Experimental strain vs. time data plotted in MATLAB® (natural response after the ball is removed).

##### 4.1. Wave Equation Results

The discretized wave equation was solved in MATLAB® for time = 3000-time steps and radius = 87 mm. Initial conditions were given in the code, i.e., quadratic profile and maximum deformation of 0.5 V (recorded by high-frequency oscilloscope from experiments; this value is directly proportional to the strain). The damping term was also added with a coefficient of damping = 0.006. After plotting the experimental and MATLAB® simulations results together, as shown in Figure 17, the wave equation predicts the profile and frequency of 205 Hz as obtained from the experiments.

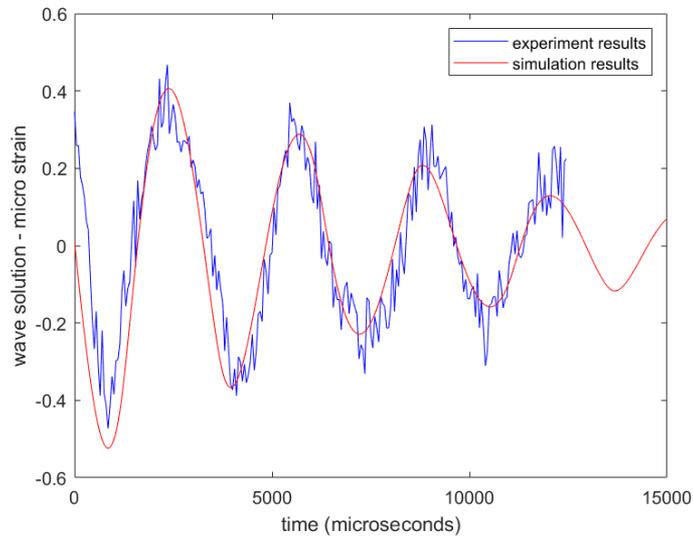


Figure 17: Strain vs. time plot of experimental and FDM, Numerical Simulations in MATLAB®.

The ANSYS® simulated results in the explicit dynamics' analysis are presented in Figure 18. The ANSYS® results exhibited an approximately equal deformation behavior and strain waveform as that observed from the physical experiments and FDM numerical study in MATLAB® as shown in Figure 19.

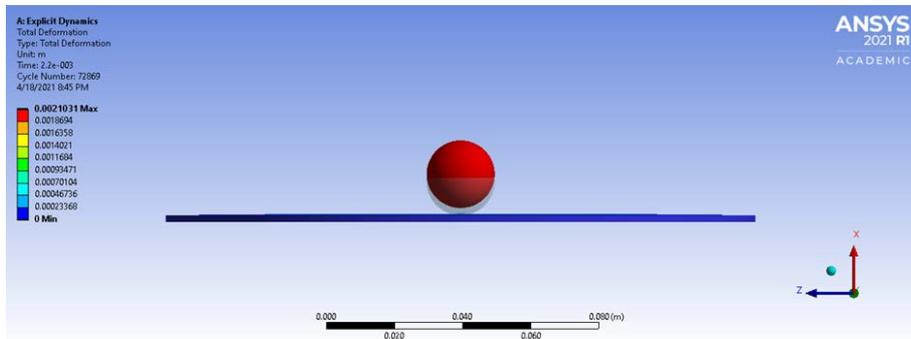


Figure 18: ANSYS® Simulation of CFRP plate vibrating upon impact with steel ball.

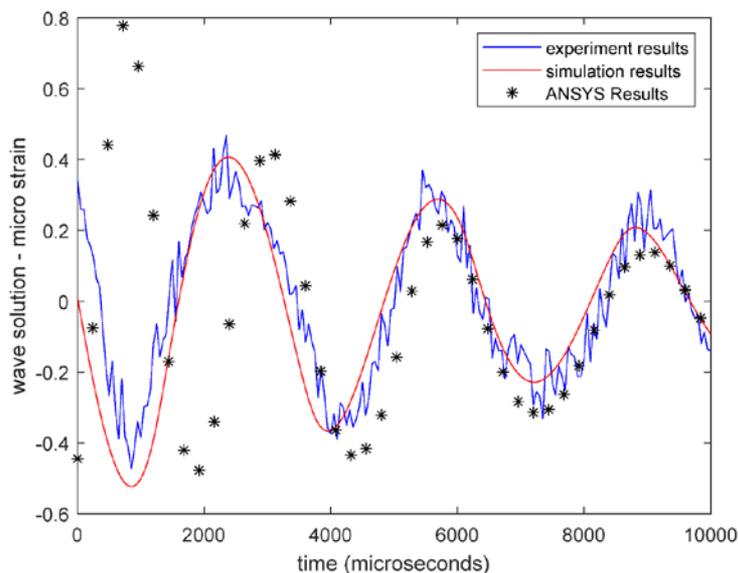


Figure 19: Strain vs. time plot of experimental, FDM Numerical Simulations in MATLAB® and ANSYS® results.

## 5. CONCLUSION

From the DWIT, it appears obvious the convenience of using op-amp circuit and high-speed oscilloscope for monitoring impact tests. Useful information about a material's behavior can be derived quickly. Experiment strain results of a fully clamped CFRP plate give a strain wave frequency of 205 Hz when impacted with a 33 g steel ball from a height of 1 m. The peak strain value recorded was 0.5 micro strain when the plate vibrates naturally. It was also observed that the strain waves undergo significant damping, and amplitude drops to 0.15 in 0.012 s. Dynamic strain reflects the behavior of CFRP under drop impact for in-plane measurement.

The elastic strain waves produced upon impact were simulated by FDM Numerical Simulations in MATLAB® and ANSYS® Explicit Dynamic Module. Results show that the elastic waves generated in a quasi-isotropic CFRP sheet were high-speed and finish in almost 0.015s due to a significant damping effect. Numerical simulations were in good agreement with the experimental findings.

## ACKNOWLEDGMENTS

Thanks to Young Kwon of the Naval Postgraduate School, Monterey, CA, USA for providing the CFRP test samples. The publication charges for this article were funded by a grant from the publication fund of UiT-The Arctic University of Norway.

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