Reliability and limitations of Impact-Echo Method for Thickness Measurement of Orthotropic Composite Plates

Mohammad Mahdi Amiri
Center of Excellence in Precision Dimensional Measurement
Technology Development Institute (TDI), ACECR, Sharif University Branch
Tehran, Iran
Email: amirimm@ripi.ir

Mohammad Tabatabaee Ghomi*
Center of Excellence in Precision Dimensional Measurement
Technology Development Institute (TDI), ACECR, Sharif University Branch
Tehran, Iran
Email: tabatabaee@usc.ac.ir
*Corresponding author

Gholam Hosein Liaghat
Mechanical Engineering Department
Tarbiat Modares University
Tehran, Iran
Email: Ghlia530@modares.ac.ir

Abstract: In this paper, an Impact-Echo method has been used to numerically simulate low velocity impact of a steel ball on laminated composite plates in order to measure the plate's thickness. For the purpose of simulation, Ls-Dyna finite element code has been employed to express the behaviour of impact between steel ball and composite plates. Furthermore, a single node near the impact area has been chosen and its displacement was demonstrated during the impact time on a graph by the software. After that, displacement-time graph was transformed to amplitude-frequency domain graph by means of Fast Fourier Transform which was done by MATLAB software. The peak frequency was used to calculate the plate's thickness. The calculated thickness was verified by real plate thicknesses and this comparison shows an acceptable agreement between simulation and experimental results.

1   INTRODUCTION

1.1. Definition and Importance of Subject

Impact-Echo is an acoustic method which has been previously used for nondestructive evaluation of concrete and masonry structures which was first invented at the National Bureau of Standards (NBS) in the United States of America at the mid-1980's. Impact-echo is a method for nondestructive testing of concrete and masonry structures, which is based on the use of stress waves, which was generated by an impact, that travels through concrete and masonry structures and is reflected by internal flaws and external surfaces. Impact-echo could be utilized to measure the location of flaws like voids, delaminations and cracks. It could provide thickness measurements of concrete slabs with an accuracy better than three percent, and it can detect inner defects. The method could be used to determine thickness or to locate cracks, voids, and other defects in masonry structures where the brick or block units are bonded together with mortar.

All of composite structures like composite plates, pipes, vessels, etc. needs periodic inspections to evaluate their structural integrity. Typical composite structures vary largely from plates and an airplane fuselage while their common defects include internal cracks, voids and delamination. There is also a large number of well-known NDT methods for composite structures, like infrared thermography, acoustic impact method, pulse-echo method and ultrasonic method. Except for the first two methods, the other methods are mainly based on the mechanical principle of stress wave propagation in the specimen.

Among these stress wave propagation methods, the acoustic impact method is the oldest one [1]. The free surface of concrete is stroke with a metal object such as a hammer or a heavy chain and an operator listens to the reflected sound. The produced stress waves are very low in frequency. This method is so time-consuming and requires an expert operator to interpret t the results. It is noteworthy that reflected sound becomes less reliable as an increment in the depth of the defect.

1.2. Explanation of References

Khalili et al. studied pre-notched basalt fiber reinforced epoxy (BFRE) composite specimens under Charpy impact loads in order to investigate the changes in impact energy absorption (fracture toughness) with different kinds of aging conditions [2]. They have inspected the nature of the failure mechanisms, by Scanning Electron Microscopy (SEM) photographs. Fernandez-Canteli et al. investigated the dynamic behaviour of three fibre fabric composite laminates by testing notched specimens in an instrumented Charpy machine [3]. Khalili et al. investigated basalt fibre reinforced epoxy and basalt fibre metal laminate composites under tensile and bending loading conditions [4]. Khazraiyan et al. used finite element method to numerically simulate impact of low-velocity specific projectiles with water surface for which they have employed Ls-Dyna finite element code. The results confirmed that the impact of structure with fluid can be modelled using finite element model with high accuracy in terms of quality and quantity [5].

One of the most well-known models for free surface simulation is volume of fluid (VoF) method which was used in this thesis. In 2008, Tveitnes and Fairlie-Clarke conducted a research on impact of wedge-shaped parts with water surface at constant velocity [6]. Habibalahi et al. the applied PEC method to the qualitative and quantitative measurements of stress in aluminium alloy specimens [7]. PEC is a high performance non-destructive testing technique but its application in stress and residual measurement is unknown. Their results indicated that pulsed eddy current responses are sensitive to stress and revealed that PEC method is capable of residual stress measurements.

In this case, the X-ray diffraction method is no longer non-destructive [8]. As a result it is always an important challenge across NDE to achieve a cheap and portable method to measure residual stress with a sufficient depth of inspection and reasonable accuracy. Herein lots of researches have been conducted for evaluation of both applied and residual stresses. Since different materials have different character for stress measurement, scientists have used different physical phenomena and different testing techniques for stress measurement such as residual magnetic field sensing for ferrite metallic samples [9], ultrasonic wave velocity variation [10], magnetic anisotropy [11], magnetic Barkhausen noise or metal magnetic memory testing [12].

1.3. Illustration of the New Work Compared With Previous Works

Impact-echo is a practical solution for flaw detection in nonhomogeneous materials like concrete slabs and masonry structures, which use mechanical impact to produce P-waves or stress waves. Impact produces high-energy waves that propagate into the test specimen. The structure which was tested by Impact-Echo must have an enough thickness to allow enough time for separation between imposing the impact and the echo arrival. More than 4mm thickness will allow enough time for round trip travel which is needed for travel distance calculation. Thus, impact response of thin plates such as slabs, is more difficult to interpret than that of thick ones. However, Impact-Echo has been widely used for flaw detection in masonry structures and slabs, but in this paper it has been used for flaw detection in composite structures.

As composite structures, have non-homogenous nature, other type of non-destructive test could not be used

because of attenuation of waves. Therefore, Impact-Echo has capability to produce stress wave because of low velocity impact and the generated waves propagate into the composite plate. These wave have long wavelength and low frequency so they are capable to travel throughout the specimen. The previous methods, which was proposed, for nondestructive evaluation of composite plate have their own limitations. In addition the Impact-Echo is a method which needs just access to one side of the plate not both sides and it could be employed for in-site inspection. Therefore, in this paper the use of Impact-Echo will be studied for measuring the thickness of composite plates which has not be done in previous and similar researches.

2   IMPACT ECHO METHODOLOGY

As it was stated before, impact on the composite plate surface produces P- and S-waves that travel into the plate and Rayleigh waves, which travel through late surface wave and away from the impact point. The P-waves (also called stress wave) and S-waves (called shear waves) are reflected by inner defects or outer boundaries. Once the reflected waves (echoes) come back to the surface, they make a very small movement in the plate surface that is measured by a receiver (transducer). If the transducer is positioned close to the impact point, the response is dominated by stress wave echoes and not shear wave. The first considerable movement at the plate surface will be initiated by the R-wave, and afterwards a series of repeating downward displacements of lower amplitude are created because of the appearance of the P-wave echoes.

Impact-Echo method send a low frequency sound, into the specimen to evaluate integrity of the member. However, some limitations exist, sound generation is an appropriate method for detecting delaminations in concrete structures and ASTM has standardized it. In NDT techniques, the ultrasonic pulse-echo (UP-E) method has proved to be a suitable method for sensing cracks and other internal flaws. In UP-E method, a transducer is used to produce a short pulse of ultrasonic waves, which transmits into the specimen. After impacting the ball on the outer surface of the plate, reflection of the stress waves happens at the specimen boundaries. The reflected wave travels back to the transducer that also takes part as a receiver. The received wave is showed on an oscilloscope, and the round trip travel time of the pulse is measured automatically. Knowing the velocity and traveling time of the stress wave, the distance between impact surface and boundaries surface could be estimated. The existence of air voids, defects, crack and flaw could also lead to stress wave reflections. In this section, we review the basic concepts of stress-wave or P-wave propagation, which

was used in impact-echo method. When an impact is applied at a point on the surface of a composite plate, like a steel ball in IE, the stress wave propagates through the plate as three different types of waves: P-wave, S-wave, and Rayleigh wave, with different velocities respectively. P-waves are a type of elastic wave, and are one of the two main types of elastic body waves that travel through a solid. In an infinite isotropic, elastic solid, the P-wave speed, Cp is related to Young's modulus of elasticity, E, Poisson's ratio v, and the material density ρ, as follows:

$$C_P = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \tag{1}$$

C_s represented S-wave which propagates with a slower velocity:

$$C_S = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{\rho 2(1+v)}} \tag{2}$$

Where:
G = the shear modulus of elasticity.
The ratio of S-wave speed to P-wave speed could be stated as a function of Poisson's ratio as below:

$$\frac{c_s}{c_p} = \sqrt{\frac{1-2v}{2(1-v)}} \tag{3}$$

For a Poisson's ratio of 0.25, which is usual for orthotropic composite plates, this ratio equals 0.58. The ratio of the R-wave velocity, C_r, to the S-wave velocity, C_s, is given as follows:

$$\frac{C_r}{C_s} = \frac{0.87+1.12v}{1+v} \tag{4}$$

For Poisson's ratio equal to 0.25, the R-wave speed is 92% of the S-wave speed.

3   FREQUENCY ANALYSIS

In the impact-echo method, time domain analysis had been used to calculate the time interval between applying the impact and arrival of the P-wave echo. As this process was frustrating and time consuming, it needed sufficient skills to identify the time of P-wave echoes. Recently, an important improvement has been achieved which make this process easier and more convenient. This is frequency analysis which was proposed to be used instead of time domain analysis for analysing waveforms. The P-wave generated by the impact reflections between the test surface and the reflecting boundary. Each time the P-wave reaches to the test surface, it makes a minor displacement. Therefore,

the waveform has a repeating form that depends on the round-trip travel distance of the P-wave. If the transducer (receiver) is close to the impacting location, the overall travel distance is 2T, while T is standing for the distance between the test surface and reflection boundary.

As appears in Fig. 1, the time between the several reflections of P-wave is equal to travel distance divided by the wave velocity. The frequency f of the P-wave arrival is calculated by the following relationship:
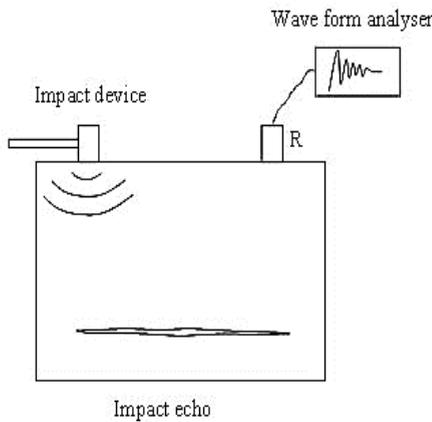

Fig. 1   Schematic of view of main concept of Impact-Echo method

$$f = \frac{C_{pp}}{2T} \tag{5}$$

Where:

C_{pp}: P-wave velocity in the plate.

T: Plate thickness (distance to the reflecting interface)

Eq. (5) expresses plate thickness frequency and is the fundamental relationship in the impact-echo concept. However, in the early researches, it was presumed that the wave velocity through the thickness of the plate was same as its velocity in other solid objects. Afterwards, it was found that [17] wave velocity relating the thickness frequency of any plate like object is almost 96 % of the P-wave velocity, that is, $C_{pp} = 96C_p$. This difference occurs as several reflections of P-waves stimulating an exact mode of vibration in the plate which is related to the plate thickness mode and the displacements in the plate surface made by this mode generate the basic periodic shapes in the waveform.

Research experiments and finite element simulations of P-wave propagation in concrete structures, covering a wide-ranging diversity of geometric shapes, have shown that for each specific shape the dominant frequency of the first mode of vibration excited by impact is related to the wave velocity C_p and a specific dimension by the following equation:

$$f = \frac{\beta C_{pp}}{2A} \tag{6}$$

Where:

β: Shape factor (depended on geometry)

As in our study we are dealing with a solid plate thickness, the specific dimension becomes plate thickness T and therefore shape factor β is:

$$T = \frac{0.96 C_{pp}}{2f} \tag{7}$$

The main objective of impact-echo frequency analysis is to determine the dominant frequencies in the reflected waves. This is accomplished by means of FFT (Fast Fourier transform) method to convert the acquired waveform into the frequency domain. The outcomes are in an amplitude range that represents the amplitudes of the various frequencies, existed in the waveform. For structures like a plate, the thickness frequency will always be the dominant frequency of peak frequency in the spectrum. The peak frequency value in the amplitude spectrum could be used to define the distance between impacting surface and reflecting surface, defined as below equation:

$$T = \frac{C_{pp}}{2f} \tag{8}$$

Fig. 2   A simple Impact-Echo system

4   INSTRUMENTATION

Nowadays industrial Impact-echo package contains the following main separable systems (Fig. 2):

1-   Impactors: a steel spheres on spring rods, used to produce the P-waves that propagate through the structure.

2-   Transducer: It is used to detect signals generated by several reflections of stress waves inside the structure.

3-   Digital Data Acquisition System: receives and digitizes voltage-time signals from the transducers, and sends them to computer.

4-   Computer: For analysing and displaying the results.

5-   DC Power Supply: As this system is portable, a chargeable power supply is required.

5   NUMERICAL MODEL AND SOFTWARE SIMULATION

Because the most IE process have been performed by experiments, replication of similar experiments could be prevented by using modelling and software simulation. For this purpose, we have chosen ANSYS-LS-DYNA software for Impact-Echo simulation and analysis. This software is a powerful tool for surface displacement measurement of the elastic deformation zone made by an impact. LS-DYNA is a general purpose and a common software to analyses the nonlinear dynamic response of two and three-dimensional structures. LS-DYNA let us to choose material properties from comprehensive material database, which seemed to be an acceptable for choosing composite materials.
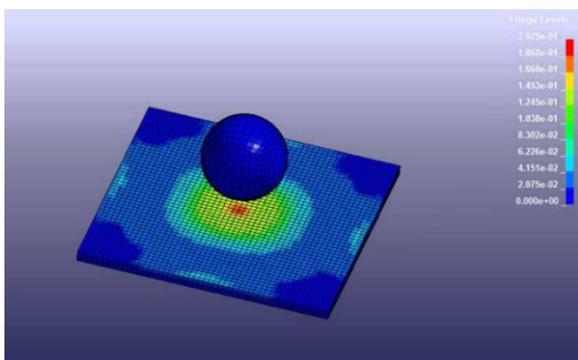

Fig. 3   Simulation of Low Velocity Impact on a Composite Plate in LSDYNA software

In this study, we proposed a measurement method for measuring composite plate thickness. Therefore, by use of this technique we can test a composite plate without the need to access two side of the plate. First of all, a steel ball is dropped at the top of a composite plate. A piezoelectric sensor, which is located on the plate at a distance from the impact location, calculates the results of the displacements reported by the sensor. As said before for performing numerical modeling, the explicit finite element program LS-DYNA was used. All of the plates and projectiles are simulated as 3D isotropic axisymmetric, models. In the model as presented in

Fig. 3 the impacting ball was modeled as a spherical projectile with specific initial velocity.

The mechanical specification of the model, used in modelling, is presented in Table 1. For simplicity in modelling we presume all the composite plates are isotropic. The Poisson ratio for isotropic plates are within the range of $0.2 \leq \nu \leq 0.5$ [18] and we consider $\nu = 2.5$ for simulation. The density of plates are $1578\ Kg/m^3$ and the module of elasticity for plates are calculated as below:

Volume fraction for fibers	V_f	28.9%	
Volume fraction for resin	V_m	71%	
Resin module of elasticity	E_m	2.75	Gpa
Fiber module of elasticity	E_f	85.00	Gpa
Module of elasticity in fiber direction	E_t long	26.52	Gpa
Module of elasticity perpendicular to fiber direction	E_t trans	3.82	Gpa
Weight of used fibers	W_f	30.00	Kg
Weight of used resin	W_m	33.00	Kg
Density fiber	2,600.00	Kg/m^3	
Density resin	1,162.32	Kg/m^3	
Density Composite	1,577.76	Kg/m^3	

P-wave velocity in the composite plates was equal to 3176 m/s.

Table 1 The mechanical properties of composite plates and impactor

Item	Young's modulus $E\ [Gpa]$	Poisson ratio ν	Density $\rho\ [kg/m3]$	P-wave speed $C_P\ [m/s]$
Steel ball	210	0.3	7850	6020
Composite plates	33	0.2	2300	4000

6   EXPERIMENTAL STUDY

The experiment has been performed by a portable impact echo system (PIES). It was intended to compare IE simulation results with machine outputs. In this paper, we have proposed a new method for composite plate measurement using impact echo system. As said before one the advantages of this new method is that there is no need to access both side of the plate for measurement. First, a small steel ball is hit top of composite plate and the sensor is located on the plate near the hitting ball location. Four composite plates with different

thicknesses have been created [5]. These plates are made of resin epoxy 828 and E-Glass fiber. These plates had been placed on free surface. The signal analyzing had been done by the impact echo system. The system was set to measure plate's thicknesses.

Fig. 4   Producing composite plates and performing Impact-Echo Test

Table 2 Specifications of Impact Echo systems

Composite Plate thickness [cm]	Impactor specification	C_p [m/s]	Transducer frequency range
6 mm 8 mm 10 mm 12 mm	Steel ball $\Phi = 10\ mm$	3176	10 KHz – 2MHz

7   RESULTS AND FINDINGS

At the first step, the program was run for the plates with different thicknesses and initial velocities. Then a node on the top of the plate has been chosen and its displacement will be saved. A piezoelectric transducer is located at a distance $\left(\frac{r}{T}\right) < 0.3$, in which r stands for distance between transducer and impact area and T represents the plate thickness. Therefore, a single node, which is selected in the simulations performed, is located at the top surface of the plated. An element was selected close to the top of the plate and then plotted in a displacement-time graph (Fig. 5).
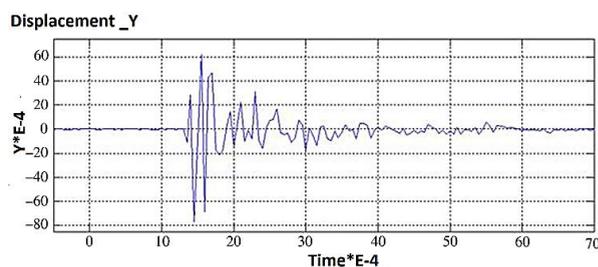

Fig. 5   Displacement versus time graph plotted by LSDYNA

The simulation data were stored in a files which were opened later by MATLAB (Table 2). Afterwards, the data will be exported in MATLAB and changed into Amplitude-Frequency graph (Fig. 6). This was achieved by use of FFT (Fast Fourier Transform) to determine a frequency analysis on the time-domain data.
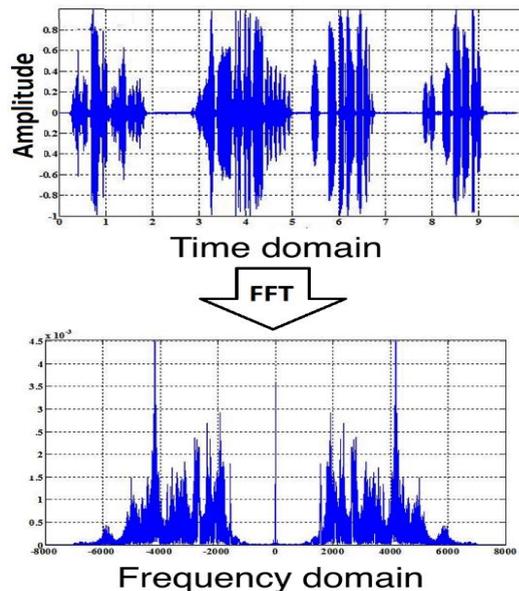

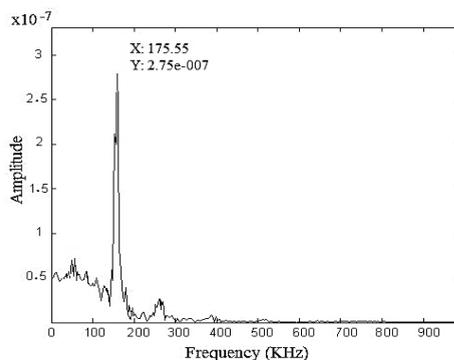**Fig. 6**   Transformation from time-domain to frequency-domain by FFT

Fig. 7   Transformed response of the steel ball impact on a 6 mm thick composite plate

It resulted into amplitude-frequency curves, which are more suitable as the dominant frequency, is easily visible. Amplitude-Frequency graph for plates with thickness of 6mm, 8mm, 10mm and 12mm is shown on the Fig. 7 to Fig. 10.
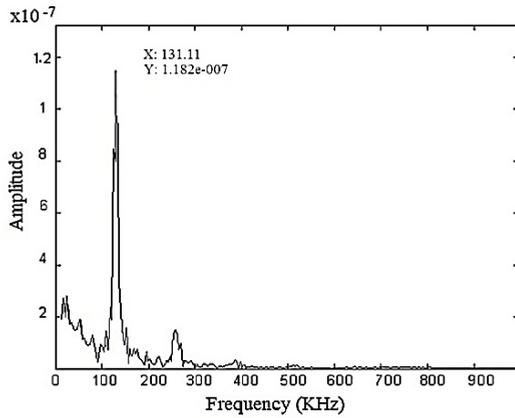

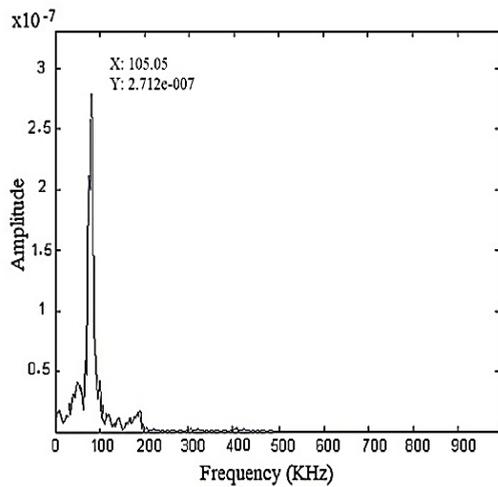**Fig. 8**   Transformed response of the steel ball impact on a 8 mm thick composite plate

Fig. 9   Transformed response of the steel ball impact on a 10 mm thick composite plate
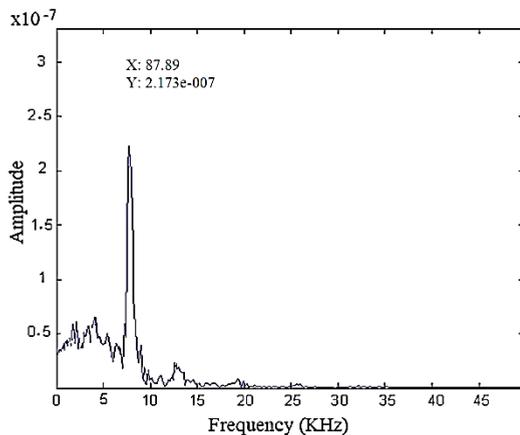

Fig. 10   Transformed response of the steel ball impact on a 12 mm thick composite plate

FFT analysis of the displacement-time could convert a simulated wave to a frequency domain graph. In a composite plate, the dominant peak in the spectrum determines the frequency that relates to the thickness and consequently is used to calculate the plate thickness in Eq. (9) which is a modified form of the Eq. (7). It is noteworthy that Eq. (7) has an experimental coefficient (0.96) but for composite plate, our findings resulted from comparison of experimental data and numerical modeling show that 0.64 is a better choice for composite plate. The analysis presented in this paper presumed that the velocity of wave propagation in the composite plate is 3176 m/s as calculated by Impact-Echo machine.

$$T = \frac{0.64C_p}{2f} \tag{9}$$

Table 3 presented the dominant frequency of FFT analysis. The difference between the numerical calculated data and the actual thickness is reflected in the last column of the table. An agreement between the thickness calculated in this study and real plates thicknesses shows that the impact echo method can be used thoroughly to measure the thickness of orthotropic composite plates.

Table 3 Verifying proposed model results

Real Plate Thickness T_R	Peak Frequency f	Calculated Thickness T_C	$\dfrac{T_R - T_C}{T_R}$
6.00	175.55	5.97	0.536%
8.01	131.11	7.99	0.240%
10.02	105.05	9.97	0.470%
12.00	87.89	11.92	0.668%

The flexural frequency of a simply supported rectangular thick plate is so formulated as below [19]:

$$ff = f_1 \times f_0 \tag{10}$$

$$f_0 = \frac{C_s}{h} \tag{11}$$

$$f_1 = \frac{1}{2}\left(\frac{1 + 3.36\lambda - \Omega}{2}\right)^{1/2} \tag{12}$$

$$\lambda = \left(\frac{T}{a}\right)^2 + \left(\frac{T}{b}\right)^2 \tag{13}$$

$$\Omega = [(1 + 3.36\lambda)^2 - 8.6\lambda^2]^2 \tag{14}$$

Where:
ff = fundamental flexural frequency,
a, b = dimensions of the composite plate,
T = thickness of the plate
C_s = shear-wave speed of composite.

The value for Poisson's ratio, ν, and K^2 in the theoretical analysis were $\nu = 0.2$ and $K^2 = 0.86$ [20], K^2 is used in the calculation of Ω. As the response to an impact is related to the mechanical properties of the plate structure, the impact–echo method has also been applied to illustrate structural health monitoring during the tests. In this research, the geometry of the plates remains unchanged unless the plates thicknesses. It was shown that the variations in resonance frequencies are directly linked to the thickness of the plates. The impact–echo method is also capable to be used to identify composite plate flaws or cracks.

Application of the impact–echo method could be extended to characterize composite materials which was already performed for concrete slabs. However, no reflection from the faults was seen in this research, but it would be possible with some modification in the current device setup which is a future topic for research in this field.

8   CONCLUSION

In this paper, it has been shown that the response of orthotropic composite plates to low velocity impact could be utilized in order to measure plate thickness. With different thicknesses, the waves produced by the impact, stimulate one or more flexural modes of vibration in the composite plates, which is related to composite plate thickness. Numerical models and specimens with different thicknesses were used to explain and quantify the response of plates. With four plates with different thicknesses and signal processing of the stress wave reflection, it was proven that impact response of plates depends on the thickness of the plates. The knowledge obtained from the numerical and experimental studies represented in this paper has provided a wider understanding of the impact-echo response of composite materials, and it has made clarification of results from plate-like structures, which may be used in building or automobile industries.

This study has been part of a research program intended to develop the theories and experiments for the impact-echo technique for non-destructive testing of composite made structures. Researches which were conducted in last two decades, mostly focused on developing the impact-echo technique for testing plates, beams and columns made of concrete. The aim of the current paper is to study the interaction of stress waves and fibers in a layered composite plate and determining the effects of plate thicknesses on the impact-echo responses. Detailed results of this research were involved both numerical and experimental studies of wave propagation in composite plates.

REFERENCES

[1] ASTM D 4580-86. Standard practice for measuring delaminations in concrete bridge decks by sounding, Annual book of ASTM standards, Vol. 04. 03. Philadelphia: ASTM, 1987. pp. 749-51.

[2] Khalili, S. M. R., Eslami Farsani, R., and Daghigh, V., "Aging Influence on Charpy Impact Behaviour of Basalt Fibre Reinforced Epoxy Composites", Int J of Advanced Design and Manufacturing Technology, Vol. 6, No. 2, 2013, pp. 81-85.

[3] Fernández-Cantelia, A., Argüellesa, A., Vina, J., Ramulub, M., and Kobayashib, A. S., "Dynamic Fracture Toughness Measurements in Composites by Instrumented Charpy Testing: Influence of Aging", Composite Science & Technology, Vol. 62, 2002, pp. 1315-1325.

[4] Khalili, S. M. R., Daghigh, V., and Eslami Farsani, R., "Mechanical Behavior of Basalt Reinforced and Basalt Fiber Metal Laminate Composites Under Tensile and Bending Loads", Journal of Reinforced Plastics and Composites, Vol. 30, 2011, pp.647-659.

[5] Khazraiyan, N., Dashtian Gerami, N., Damircheli, M., "Numerical Simulation of Fluid-Structure Interaction and its Application in Impact of Low Velocity Projectiles with Water Surface", Int J of Advanced Design and Manufacturing Technology, Vol. 8, No. 2, 2015, pp. 81-90.

[6] Fairlie-Clarke, A. C., Tveitnes, T., "Momentum and Gravity Effects During the Constant Velocity Water Entry of Wedge-Shaped Sections", Ocean Engineering, Vol. 37, No. 5, 2008, pp. 706-716.

[7] Habibalahi, A., Safizadeh, M. S., "Application of Pulsed Eddy Current Technique in Stress and Residual Stress Measurement", Int. J of Advanced Design and Manufacturing Technology, Vol. 7, No. 1, 2014, pp. 67-74.

[8] Blodgett, M. P., Nagy, P. B., "Eddy Current Assessment of Near-Surface Residual Stress in Shot Peened Nickel Base Superalloys", Journal of nondestructive evaluation, Vol. 23, 2004, pp. 107-123.

[9] Wilson, J. W., Tian, G. Y., and Barrans, S., "Residual Magnetic Field Sensing for Stress Measurement", Sensors and actuators A, Vol. 135, 2007, pp. 381-387.

[10] Hughes, D. S., Kelly, J. L., "Second Order Elastic Deformation of Solids", Physical review, Vol. 92, 1953, pp. 1145-1149.

[11] Langman, R. A., Mutton, P. J., "Estimation of Residual Stresses in Railway Wheels by Means of Stress Induced Magnetic Anisotropy", NDT & E International, Vol. 26, 1993, pp. 195-205.

[12] Wang, P., Zhu, L., Zhu, J., Ji, L., Wang, T., Tian, G., and Yao, E., "An Application of Back Propagation Neural Network for the Steel Stress Detection Based on Barkhausen Noise Theory", NDT & E International, Vol. 55, 2013, pp. 9-14.