Non-destructive Evaluation of Glass-Epoxy Composite using Impact-Echo Method

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Abstract: In this paper a new method for Non-destructive testing or Non-destructive evaluation is proposed for Glass-Epoxy composite. For this purpose, impact-echo was used to investigate thickness and integrity of composite plates. First of all, 4 composite plates were made of epoxy and fiber glass with different thicknesses (ranging from 8 to 12mm) which one of them contains predetermined internal flaw. Afterwards Impact-Echo device was utilized to detect plate thickness and internal flaw. This process was modeled in ANASYS/LSDYNA software and displacement-time graphs were obtained from the simulation. The obtained data were transferred from displacement-time to frequency domain graphs by means of FFT. The thickness of the plates which were obtained from this simulation were in good agreement with experimental data. Results represent that this method could be used for thickness measurement and flaw detection of Epoxy-Glass composites with an acceptable accuracy.

Keywords: Composite plates, Impact-Echo, Non-destructive test (NDT), P-Wave

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1 INTRODUCTION

Nowadays, nondestructive evaluation is of high importance as it could prevent major failure in industrial structure and machineries. Many attempts have been made to make nondestructive evaluation methods more reliable and practical. As a long time has not been passed from introduction of composite material into industrial applications, there is a need for more studies and investigation to recognize proper methods for testing and evaluation of these materials. Because the use of composite materials has been extended in different structures like aerospace, automobile, sailing and construction, several nondestructive methods has been proposed for evaluation and testing of these materials which all of them have their own pros and cons. Considering the mentioned requirements, in this paper an impact based method, called Impact-Echo, which has not been previously used for nondestructive evaluation of composite structures, will be studied for composite plates.

Generally, Impact-Echo has been used for concrete and masonry structures where low-frequency stress or P-waves from 1 to 60 kHz are transferred into the structures by an impact from a small steel balls [1]. As the generated waves have long wavelengths, when scattering or aggregating, small cracks and faults are less detectable in comparison with other similar method like ultrasonic or pulse-echo testing in which frequencies varies from 60 to 200 kHz. In Impact-Echo, an impact is applied on the test surface. After that a transducer measures the reflected wave from the outer surface or boundaries in an area close to impact source. Therefore, in this testing method, acoustical waves (higher than 50 kHz) are generated by a small steel ball impact on the surface of the test specimen.

These stress waves travel into the structure as three different forms; dilatational or P-wave and distortional or S-waves and along the structure surface as a Rayleigh or R-wave. The dilatational and distortional waves propagate into the structure with a hemispherical front, and if any interface exist under the test point, then elastic waves will reflect back between the surface and that interface. This impact response of the inner layer is detected by a transducer placed close to the impact source. As a result of various reflections of waves between the impact surface and other boundaries, the time-domain signal displays a time-based periodicity. Therefore, by means of fast Fourier transformation (FFT), the signal is transformed into the frequency domain. After the transformation, significant peaks in the amplitude spectrum are related to the depth of defect or the outside boundaries. Consequently, the Impact-Echo method defines the resonance modes of the testing specimen. It has been shown that for every shapes, the first mode of vibration excited by impact is obtained by following relation:

$$f = \frac{\beta C_P}{2A} \tag{1}$$

Where CP is the wave speed, A is characteristic dimension and β is a shape factor (which is determined by structure geometry). It is noteworthy that when we have a solid plate, thickness T is considered as the characteristic dimension and is calculated as below [1]:

$$T = \frac{0.96 C_P}{2f} \tag{2}$$

One of the advantages of using Impact-Echo is that there is no need to have access to both side of specimen. For some buried plates in which there no access to other side, this method could be applied effectively. In this study, we propose a new measurement and defect showing method for composite structures that uses a small steel ball which generate stress wave by means of physical impact. Accordingly, by using this method, we could conduct a non destructive test for a composite plate in site with a method which could provide quick and reliable results.

2 LITERATURE REVIEW

Impact-echo method has been used for non-destructive evaluation and non-destructive testing for masonry and concrete structures since two decades ago [1]. The impact echo method is based on a frequency analysis of P- waves which were generated by a steel ball impact. This method is commonly used for thickness measurement of concrete structures, to detect flaw inside the concrete structural elements and other masonry constructions. Hsiao et al., [2] have investigated the impact response of concrete blocks and perused the applicability of this method as a non destructive test for flaw detection in concrete structures. They have also conducted numerical studies to gain the transient responses of intact concrete blocks. Wang et al., [3] proposed a new method to evaluate Poisson's ratio of materials with the impact-echo test on a circular rod.

In this approach both the longitudinal and guided wave propagation theories were used to gain required equations by means of regression analysis. Impact echo has also been used as a non contacting NDT method for flaw detection in concrete structures. In this method, dynamic response of concrete slabs under impact loading has been utilized for flaw detection in concert structures [4]. Tabatabaee et al., [5] proposed new method for measuring the thickness of concrete plates by means of indirect Impact-Echo. In this research, a steel ball impacts on a steel bar and the stress waves travels into to the concrete plate. Numerical simulations have also been conducted for different plate thicknesses. The results showed that the impact response of the concrete plate for a known thickness frequency in the indirect method are in good agreement with the results acquired in the classic direct method. Villain et al., [6] employed Impact-Echo method on reduced size slabs (0.5 x 0.25 x 0.12 m 3). As a consequence, they identified the frequencies corresponding to resonance modes. This modal analysis was done with a simple model in order to obtain dynamic Young’s modulus.

Stavroulakis [7] studied the reflection of elastic waves from subsurface interlayer unilateral cracks by dynamic boundary element method (BEM) joint with a linear complementarily problem (LCP) formulation. The effect of the individual crack on the impact-echo response is studied and verified by numerical experiments. Kim et al., [8] studied impact-echo method as a new approach for evaluating the integrity of shafts. They have also conducted simulations of the impact-echo method both numerically and experimentally. A one-dimensional finite element simulation was done for mock-up shafts which in those some solid and damaged shafts were existed. It was indicated that the results of the experiment were in an acceptable agreement with those of numerical studies, and the accuracy of the impact-echo method was influenced by the type, size and location of flaws.

3 NUMERICAL MODELS

For numerical modeling of the problem, finite element software was employed. All plates and projectiles were simulated as axisymmetric, isotropic models. As shown in Fig. 1 projectile was modeled as a spherical ball with a known initial velocity. The condition of impact between projectile and plate determines the characteristics of the generated P-wave.

Choosing an appropriate initial velocity for projectile is of high importance because clear pick in FFT diagram is depended on it. For evaluation plates with different thicknesses, the following initial velocities were chosen as they yielded more clear results.

- 9 m/s for plate thickness of 6 mm.
- 14 m/s for plate thickness of 8 mm.
- 20 m/s for plate thickness of 10 mm.
- 25 m/s for a plate thickness of 12 mm.

For performing simulation, the following assumptions were considered. The composite plates were made of E-Glass woven fabric fibers, Epoxy 828 with solvent and TETA (10%) Hardener (Fig. 2). Each of the plates had 1925 mm long and 970mm wide with different thickness as shown in Table 1.

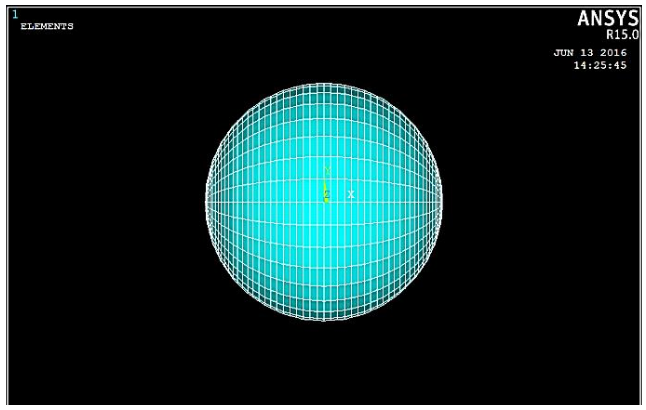

Fig. 1 The 3D model of projectile and plate and Mesh generation

As the fiberglass composite plates are isotropic regarding the study which was conducted by Mot and Ronald [9] Poisson Ratio ranges between 0.2 and 0.5. Therefore for purpose of comparison between this work and previous studies we consider 0.25 as the composite plates Poisson ratio.

Table 1 The experiments Setup

No. of Experiment	Impactor Initial Velocity m/s	Plate Thickness mm
1	9	6
2	14	8
3	20	10
4	25	12

The plate density is 4165 kg/m3 and young modules according to available samples in the global market is estimated to be 35 Gpa [10]. Therefore the mechanical properties for steel ball impactor and fiberglass plates which were used in simulation are shown in Table 2.

Table 2 Mechanical Properties of Steel Ball and Fiberglass Plates

Mechanical Properties Components	Young’s modulus (E) GPa	Poisson ratio (υ)	Density (ρ) (kg/m3)	Sensor Specification
Steel Ball Impactor	210	0.3	7850	10 KHz to 2 MHz (Transducer range of frequency)
Fiberglass Plates	35	0.25	4165	

The stress wave or P-wave speed is calculated by using a formulation which was provided in reference [1] which is given by the following equation:

$$C_P = \sqrt{\frac{(1-\nu)E}{(1+\nu)(1-2\nu)\rho}} \tag{3}$$

By means of equation (1) and data which was provided in Table (2), the P-wave speed for steel ball impactor will be equal to 6001 m/s and for fiberglass plates C_P are 3176 m/s. According to what mentioned in previous work for sensor frequency, time interval of the displacement is considered to be 1.334 µs [11].

4 METHODOLOGY

In many applications there is no access to both or even one surfaces of a plates, i.e. when plate is buried in soil or has been installed in a structure. In order to perform the test, a steel ball projectile and composite plate have been modeled. All the elements in this simulation were considered axisymmetric, 2D and isotropic. For all considered thickness the element size in all distances from edge of plate to the testing place was 2.5mm and these sizes were 5mm to the end of the plate. In the model just the bottom surface of the plate was fixed along 'Y' axis, and the other sides of the plate had free boundaries; thus, axisymmetric models employed the unchanged boundary conditions. According to the testing equipment, time interval of the displacement data acquisition was 2.668ms. Final time for any simulation process was as long as 2048 times of the interval time. While number of data approached 2048, the displacements would be equal to zero. Therefore, to increase the resolutions of the FFT analysis and make it more clear, a number of zeroes at the end of the data record size were added. With this approach four times of the time domain would be obtained (8192).

5 EXPERIENT

The experimental activities were done in Tarbiat Modares University, by a portable impact echo machine which was made by PIES Company. This experimental study was intended to investigate if impact echo system works for composite plates or not. These composite plates were made with those physical characteristics which were used in simulation method. As the system eliminates some of the unwanted waves, we could consider an experimental model with a smaller diameter than the simulation model. The composite plates were lied on their free surfaces.

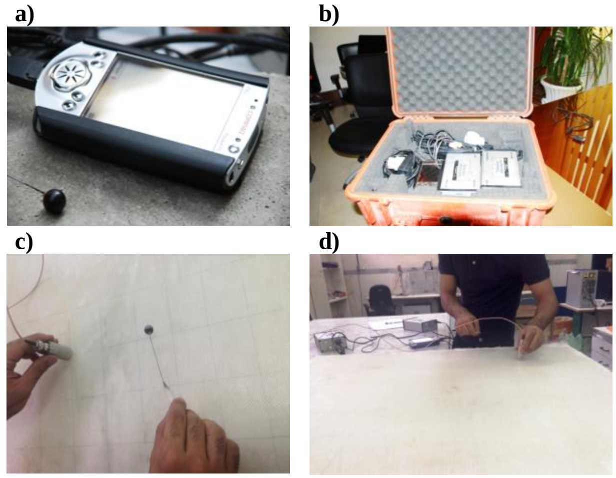

Fig. 3 Experimental set-up. a, b) Portable IE system C, d) test procedure

A spherical steel ball was employed for imposing impact on the plates. The PIES system was capable to perform signal analysis too. PIES machine was normally used for measuring thickness, computing concrete specifications and identifying crack location. In this research this machine was set up for thickness measurement and the results were obtained in Excel files and frequency-amplitude graph. Fig. 3 shows arrangements for the proposed method of composite plate thickness measurement. For this purpose, a small steel ball was knocked at the upper surface of the composite plate.

6 OUTCOMES AND DISCUSSION

When the P-wave touches the bottom of the composite plate, the S-wave is in half of its way to the lowest point of the plate. When the reflection of the P-wave is in half of its way to the top of the plate, the S-wave touches the lowest point of the plate. This is in agreement with what has been stated in previous works [1].

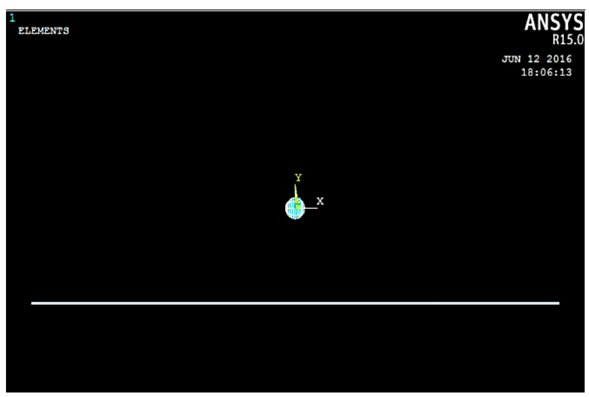

Fig. 4 Finite element simulation of impact on a plate

A piezoelectric transducer is located at an appropriate distance from the position of the impact on upper side of the composite plate. The perpendicular displacement is documented by the transducer. Therefore, in our simulations, a single node is considered at the top surface of the plate within a certain distance (r) from the position of the impact to receive the reflected waves from the other boundary of the plate. The acquired data from ANSYS/LS-DYNA simulation are in the displacement–time curve (Fig. 4). It is not easy to take necessary information from these curves as the time interval of impact wave propagation between the upper and lower boundaries of the composite plates is difficult to detect. The FFT (Fast Fourier Transform) could be employed to determine a frequency analysis on the time-domain data. By using amplitude–frequency curves instead of displacement–time curves, resulting data like plate thickness or void locations would be more accurate and reliable. Fig. 5 represents an example of this concept.

To explain the effect of distance between impactor and the receiver on the thickness-amplitude, the time-history of nodal perpendicular movements at different r/T ratios of the designed models was recorded [12]. When the transducer is very close to the location of impactor, the P-wave does not have enough time to be divided into the S- and R-waves prior to reaching to the transducer. Moreover, the impact can remove the connection between transducer and the plate. On the other hand, if the transducer be located far from the impactor, P-wave reflections from lower boundary of the plate may interrupt the integrity of the R-wave. Therefore, a ratio of $r/T = 0.3$ was selected to compensate these two unwanted effects. This ratio guarantees that the amplitude of the displacements generated by the P-wave arrival at the transducer is strong enough for arrival identification.

Figures 6-9 represent the results for those nodes which were located at $r/T = 0.3$. By means of FFT analysis, displacement–time waveform will be transformed to a frequency domain curve. In a composite plate, the dominant peak in the spectrum shows the thickness frequency which was used to determine plate thickness by aid of Eq. (1). Figure 9 represent that with the numerical analysis of a plate with 12 mm thickness, the dominant frequency would be 126.93 KHz. These findings are in complete agreement with the previous studies [12]. For calculating thickness by dominated frequency we have to use Eq. (2) which was stated in first section of this paper. Fig. 6-9 demonstrate the amplitudes of Impact Echo tests on composite plates with different thickness. By increasing the plate thickness, impactor velocity should also be increased to allow the impact waves gain sufficient energy to pass through the composite plate. Despite of amplitude difference, the resulting thickness frequencies are approximately same in all plate thickness. This similarity indicates that the thickness frequency is independent of the input wave energy. Table 3 summarizes the overall results of Figures 6-9. The difference between the measured and the actual thickness is reflected in the last column of Table 3. As the differences are negligible this new method is verified.

Table 3 Comparison between the results of the analytical obtained thickness and real thickness

Actual plate thickness $T(mm)$	thickness frequency $f\ (\frac{1}{s})$	thickness by formula $T_d(mm)$	$T_d - T$	Error Percentage
6	254.08	6.000	0.000	0.0000
8	189.73	8.035	0.035	0.0003
10	154.46	9.870	-0.130	-0.0010
12	126.93	12.010	0.010	0.0000

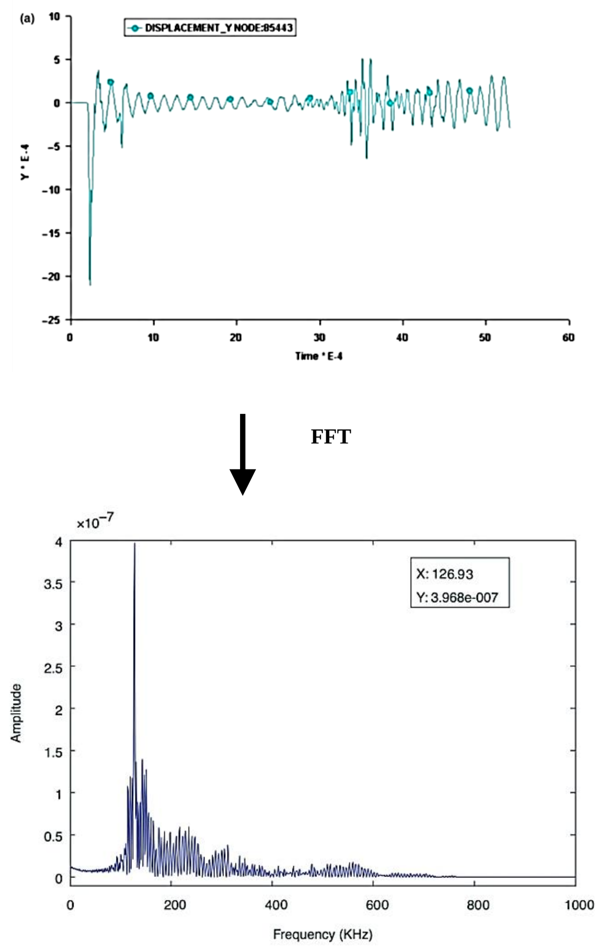

Fig. 5 Transformation from time-domain to frequency-domain for a composite plate with thickness of 12 mm

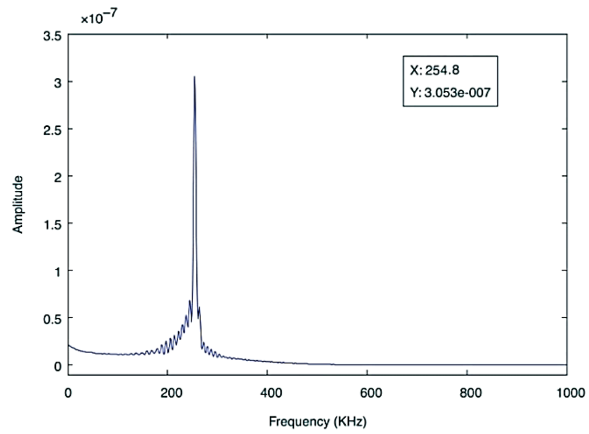

Fig. 6 Numerical response of a composite plate with thickness of 6 mm

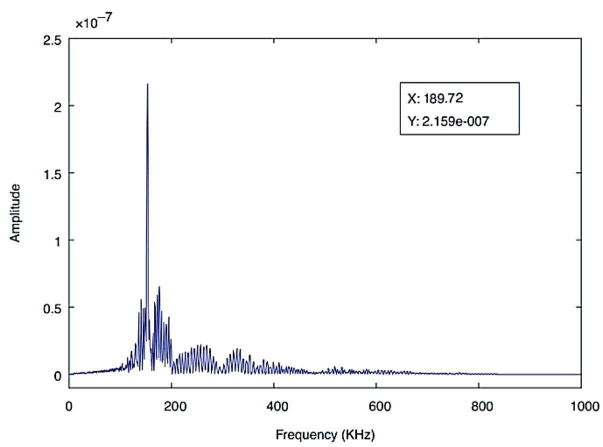

Fig. 7 Numerical response of a composite plate with thickness of 8 mm

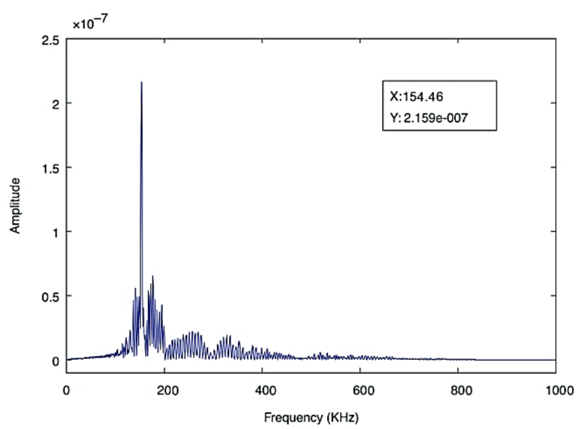

Fig. 8 Numerical response of a composite plate with thickness of 10 mm

The difference between real and experimental data happened as minor difference in composite samples. These results indicate that while the amplitude is different, the same peak frequency was observed. Several experiments were carried out and it was found that the place of the impact is important and impact place may result to some differences in the results. Some errors were originated from impact point displacement in the IE method. Some other errors did not appear in some experiments and they were accidental.

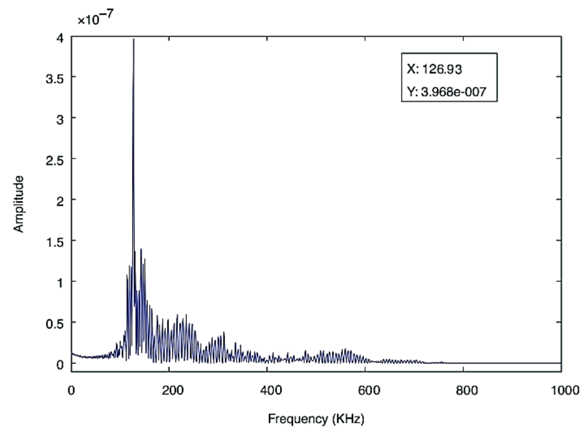

Fig. 9 Numerical response of a composite plate with thickness of 12 mm

7 CONCLUSION

In this paper, a new method for measuring composite plate thickness was presented. Several simulations on the composite plates with different thicknesses were carried out by means of ANSYS/LS-DYNA software. Experimental investigations were done on composite plates by an Impact Echo device. All the simulation results and experimental data represent that measuring results of this method are in good agreement with traditional measuring methods. Moreover, finite element study of the IE method was successfully implemented to measure the thickness of composite plates. This method has advantages over the other measuring method where there is no access to both side of a structure. The acquired data are in an acceptable agreement with real measurement results and this shows that this method could be employed to measure the thickness of composite plates and other composite structures in which there is limited access to the surface of the plate. The numerical calculations demonstrated to be a helpful tool for IE method understanding and determination the locations of physical voids. Finally, from the experimental results and simulations, it is concluded that however impact echo has previously used for measurement and non destructive evaluation of masonry and concrete structures but it could be employed for thickness measurement of composite structures. The potential of this technique for other applications for example crack detection could be considered as the subject of future researches.

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