The Impact-Echo method applied to the auscultation of bridges: Numerical study

Hajer Rezgui Chaabouni[1], Sylvie Yotte [1], Mokhfi Takarli [1]

[1] GC2D laboratory, Egletons, France

Contact e-mail : hajer.rezgui@unilim.fr

ABSTRACT: Impact-Echo is a non-destructive method used to determine thicknesses and locate defects in concrete or masonry structures. It has already been proven to be quite efficient for the evaluation of concrete plates, and is still to be developed for masonry structures. While previous studies have mainly focused on detecting and locating defects in single-layer plates, and evaluating the bond quality at internal interfaces in the bilayer ones, the identification of defects located in the second layer of a bilayer plat has yet to be explored. The purpose of this study is to investigate the capabilities of Impact-Echo method to identify defects located in the 'second layer' (the head walls or the vaults being the first one and the fill being the second one). In this study a full numerical factorial design based on four factors namely: reflection coefficient, thickness of the first layer, depth of the defect, and damping coefficient; is conducted to evaluate the Impact-Echo response of a bilayer plate containing a defect. Among the four factors, only the damping coefficient seems to not affect the interpretation of an Impact-Echo test. However, the three other factors could potentially influence the response of an Impact-Echo test. Primary results of the numerical design of experiments the will be presented.

1 INTRODUCTION

This paper falls within the framework of the evaluation of masonry bridges. Studies conducted by Bell, (2004) and Proske et al. (2009) have shown, that the majority of European masonry railway bridges inspected are over 100 years old and that 58% of them are in a medium to a degraded state. The residual life of these bridges is therefore an important economic and social issue. In order to evaluate it, one seeks to establish a 'state of health' using methods that would provide information on the existence or the absence of defects within structures without deteriorating them. The type of defect that draws our attention in this study is the void located in the filling. In fact, the deterioration or loss of materials in this filling can directly or indirectly affect the behavior and safety of the bridge structure. One of the main difficulties encountered is the ability to inspect the fill located beyond the vault and the head walls without degrading the structure being inspected. The deterioration or the material loss in the filling can directly or indirectly affect the behavior and the safety of the structure. An adequate evaluation is therefore essential to preserve the heritage and ensure the safety of the users. Auscultation methods are numerous and can provide different, yet complementary information. The Impact-Echo method, initially developed by Sansalone et al. (1986), is defined as a non-destructive method for the evaluation of structures based on the exploitation of compressional waves generated by impact. These waves propagate through the medium and are reflected by defects, internal interfaces and external surfaces of the structure. The Impact-Echo method, can be used to determine thicknesses and/or locate defects in structures. The surface displacements caused by the reflected wave arrival are measured by a transducer, near the point of the impact. The resulting signals as function of time are transformed in the frequency domain. The multiple reflections of compressional waves between the impact surface, the defect, the internal interfaces, and the external surface give rise to transient resonances Sansalone et al. (1997), that can be identified from the frequency spectrum and used to evaluate the integrity of the structure. The frequency of the compressional wave arrival, which is approximately the inverse of the time elapsed between the moment of the impact and the arrival of the compressional wave, is given by Eq.(1), V_p being the compressional wave velocity, P the thickness of the evaluated structure, β the shape factor and n a factor depending on the acoustic impedances of the layers constituting the bilayer medium.

$$f = \frac{\beta V_p}{nP} \tag{1}$$

Impact-Echo has been successfully applied for accurately measuring thicknesses of concrete plate (Azari et al. (2014); Chaudhary, (2013); Sansalone et al. (1986); Sansalone et al. (1997)) and masonry brick walls (Sadri, (2003); Sangoju et al. (2009); Sansalone et al. (1997)). It also have been applied for detecting and eventually locating defects such as voids, cracks, delamination, honey combing and different type of inclusions in concrete or masonry controlled defects structures (Chaudhary, (2013); Sangoju et al. (2009); Sansalone et al. (1997)). Sansalone and Streett, (1997) also used Impact-Echo to evaluate the bond quality between two layers of a bilayer structure such as concrete bridge decks with asphalt overlay and concrete shaft liners in contact with rock. As mention previously, Impact-Echo studies have mainly been focusing on detecting defects locates in the same medium where the impact has been applied. Previous studies do not take into account the possibility of a defect located deeper than the first interface, a case that is frequently encountered when evaluating large structures, such as masonry bridges, where a compression wave must sometimes cross more than one interface before reaching the defect. In this paper, the main focus will be on detecting defects located in second layer of a bilayer plate. We choose to investigate this issue through numerical simulations in order to develop a methodology for analyzing the signal. Later, we will compare the results to a real case. In this paper, only the numerical part is presented. In a first part, we will present the simulation and the design of experiments. Then in a second time, an analysis of the results is drawn which shows the influence of each parameter.

2 NUMERICAL MODELLING

2.1 *Finite Element Study*

The Finite Element method (FE) has been explicitly used to simulate the wave propagation in solid media (Huang et al. (2010); Pradhan, (2014); Sansalone et al. (1986); Sansalone et al. (1997); Serón et al. (1990)). Few authors such as Topping et al. (1991) have used the FE method to study the response of the Impact-Echo method applied to materials such as masonry. For finite element calculations applied to the Impact-Echo study, all materials are modeled as elastic, isotropic and homogeneous materials. These assumptions are valid for frequencies below 80 kHz. Indeed, and as explained by Sansalone et al. (1997) linear elastic models are valid for structural materials such as concrete, stone, masonry and steel, at low level of deformations produced by impact generated waves for an Impact-Echo test. These mechanical waves typically have frequencies below 80 kHz and wavelengths ranging from several centimeters to few meters. At these wavelengths, materials such as concrete, masonry, rocks or asphalt appear homogenous to the propagating wave and can be therefore modeled as homogenous isotropic materials. As mentioned previously, the aim of this study is to evaluate the ability of the Impact-Eco method to determine the existence of the defect and if possible, locate it. To do this, a design of experiments will be conducted. The simulations will be realized with Cast3m© software, providing finite element calculation for structural mechanics and fluids.

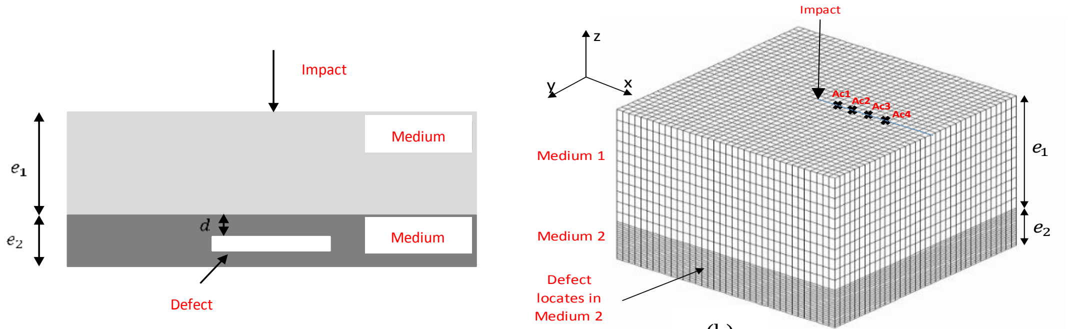
2.2 *Numerical modelling*

In the Impact-Echo method, the mechanical waves are introduced by an elastic impact of a metallic sphere in a solid surface. This impact can be represented by any force that varies rapidly with time (Sansalone et al. (1986)). In this study, the impact is represented by a half-square sine (Eq.(2)) and the response is measured on a set of points near the impact as shown in Figure 1. The positions of the measurement points meet the criterion proposed by (Sansalone et al. (1986)) which states the distance between the impactor and the receiver should be located between 20% and 50% of the thickness of the evaluated plate-like structure. The impact parameters are presented in Table 1. F_{max} is the maximum force and t_c is contact time of the impact.

$$F(t) = F_{max} sin^2 \left(\pi \frac{t}{t_c} \right) \quad (2)$$

Table 1. Loading input parameters

Parameters	$d\ (cm)$	$t_c\ (\mu s)$	$F_{max}(N)$
Values	2	86	1700



(a) (b)

Figure 1. (a). Longitudinal cut of simulated bilayer geometry
(b) Geometry of the simulated bilayer on Cast3m

Figure 1.(a) shows a scheme of the simulated problem, with some of its geometrical parameters (depth of the defect d, thickness of the first layer). The finite element modeling of this geometry is shown in Figure 1.(b). The first medium corresponds to a solid medium having parameters that can be associated with concrete or masonry. The second one corresponds to a medium that can be associated to a filling such as soil or sand. The defect is located in the second medium. Such parameters are chosen in order to be placed in conditions of real structural materials. The temporal response is transformed into the frequency domain by using the mathematical function 'Fourier Transform'. The distribution of frequencies produced by the impact can be obtained by applying the Fourier Transform on the half squared sine curve. Experiences (Sansalone et al. (1997)) have shown that approximately above $1.25/t_c$ (14.5 kHz in our case) the frequency spectrum is not useful. Frequency analysis is the primary approach for interpreting the response measured following an Impact-Echo test. The important frequencies appear as distinct peaks in the frequency spectrum. However, in a finite bilayer medium containing defects, the generated wave will be reflected by the internal interfaces between the two layers, the defect, the external interfaces and the lateral edges. All these reflections will inevitably lead to the appearance of several frequency peaks, which can distort the results interpretation and leads to confusing the

meaning of each peak. The frequency spectrum being already quite complicated to analyze, several frequency peaks due to different modes of vibration can occur. Indeed, an impact applied to a finite medium can excite various modes of vibration, such as cross-sectional, longitudinal, flexural and torsional modes (Sansalone et al. (1997)). The frequency spectrum obtained from an Impact-Echo test conducted on a bilayer medium containing defects will become quickly incomprehensible and the readings will become unreliable. Because of this, one cannot rely on the position of the peaks reading alone in the frequency spectrum and new parameters must be introduced.

2.3 *Numerical design of experiments*

A full factorial numerical design based on four factors is conducted (Table 2). The aim of this numerical design of experiment is to evaluate the Impact-Echo response of a bilayer plate containing a defect. In this study, different factors suspected to affect the numerical response of an Impact-Echo simulation will be considered. Four main input factors are selected. These input factor values were not randomly chosen. As a matter of fact, each input factor depends on several parameters that will be explained in the next section.

Table 2. A full factorial numerical design

Factors	**Reflection coefficient R**	**Thickness of the first layer e_1 [m]**	**Depth of the defect d [m]**	**Damping coefficient ξ**
Levels	0.45	0.25	0.07	0.0001
	0.71	0.375	0.0875	0.0002
	-	-	0.105	0.0003

2.3.1 Reflection coefficient R

Measuring the depth of an interface between two layers with different acoustic impedances is only possible if the reflection coefficient of the propagating wave is sufficient. Sansalone et al. (1997) states that an absolute value of the reflection coefficient R must be greater than 0.24 (Eq.(3), Z_1 and Z_2 are the acoustic impedances of the first and the second medium respectively). Otherwise an interface is a priori not detectable. The chosen values for the coefficient of reflection are superior to the established limit. Two levels are considered. The low level of this factor ($R = 0.46$) corresponds to a bilayer composed of a rock as a first layer and soil as a second one. The high level ($R = 0.71$) of this factor corresponds to a bilayer composed of concrete as a first layer and soil in the second one.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{3}$$

2.3.2 Thickness of the first layer e_1

The chosen values for the thickness of the first layer in this numerical design of experiments corresponds to values greater than the minimum between the half of the minimal wavelengths corresponding respectively to the materials constituting the first layer of the bilayers (having a reflection coefficient $R = 0.46$ and $R = 0.71$). Indeed, for an interface to be detected, the latter must be located at a minimum depth (Eq.(4)). Several authors such as Bitri et al. (1996); Martin et al. (1998); McCann et al. (2001) and Sansalone et al. (1997) agree that for a given wavelength, an interface (or a defect) can be located if situated at depth greater than the half of the minimal wavelength $\lambda_{min}/2$ of the propagating wave. As the interest of this study focuses on the detection of the defect located in the second layer, we place ourselves in conditions where the interface between the two mediums is a priori detectable in order to not further complicate the interpretations.

$$e_1 > min\begin{cases} \frac{\lambda_{min1R=0.46}}{2} \\ \frac{\lambda_{min1R=0.71}}{2} \end{cases} \tag{4}$$

2.3.3 Depth of the defect d

Since the selected values of the depth of the defect d are based on the same principle as the thickness of the first layer, the values of this factor corresponds to values greater than the minimum between the minimal half the wavelength of the second layer of the bilayers respectively with reflection coefficient $R = 0.46$ and $R = 0.71$.

$$d > min\begin{cases} \frac{\lambda_{min2R=0.46}}{2} \\ \frac{\lambda_{min2R=0.71}}{2} \end{cases} \tag{5}$$

2.3.4 Damping coefficient ξ

The damping coefficient is involved in the Rayleigh damping implemented in the Cast3m code. Unlike the pure viscous or hysterical damping, the Rayleigh damping takes into account the overall damping translating the dissipation of energy in the physical system. Preliminary test conducted in the laboratory while developing the numerical code have shown that the damping coefficient of a concrete medium is about 0.0002. Three values around the damping coefficient of a concrete medium are then considered.

3 NUMERICAL RESULTS ANAYLISES

The signals collected on the surface (Figure 1) are treated in the time domain and processed to the frequency domain using Matlab®. The collected time data is windowed to remove the Rayleigh wave as suggested by Medina et al. (2007). The temporal window used is the Blackman-Harris window. Once the windowing is applied, and the temporal response transformed in the frequency domain, the *Multicross-Spectral Density* (MSD) is calculated. Further details on the MSD use can be found in Medina et al. (2007). Only the frequencies with high amplitudes in all spectra, that is, the frequencies related to the response of the structure will have a high amplitude in the MSD.

3.1 Effect of the damping coefficient on the Impact-Echo response

In this section, three values (Table 3) of the damping ξ were selected in the numerical testing in order evaluate the effect of its variation on the frequency response. As shown in Figure *2* this variation only affect the amplitude of the spectrum and do not influence the frequencies. Therefore, the damping coefficient do not affect the interpretation of an Impact-Echo test.

3.2 Effect of the Reflection Coefficient on the Impact-Echo response

As detailed previously, the two selected levels (Table 4) of reflection coefficient R represent two bilayers having different materials with different properties. Therefore, differences between the two responses are expected. For the input data corresponding to Test 5 with a coefficient reflection $R = 0.71$, the interface frequency calculated by (Eq.(1)) is 12.1 kHz and the defect frequency is 6.5 kHz. The two dominant frequencies for the numerical Test 5 as seen in Figure 3 can be representative of the interface and the defect frequency. For the input data corresponding to Test

1 with coefficient reflection R=0.46, the interface frequency calculated by (Eq.(1)) is 7.8 kHz and the defect frequency is 4.6 kHz.

Table 3. Summary of the selected tests

Tests / Factors	Test 5	Test 25	Test 13
R	0.71	0.71	0.71
e_1 **[m]**	0.25	0.25	0.25
d **[m]**	0.07	0.07	0.07
ξ	**0.0001**	**0.0002**	**0.0003**

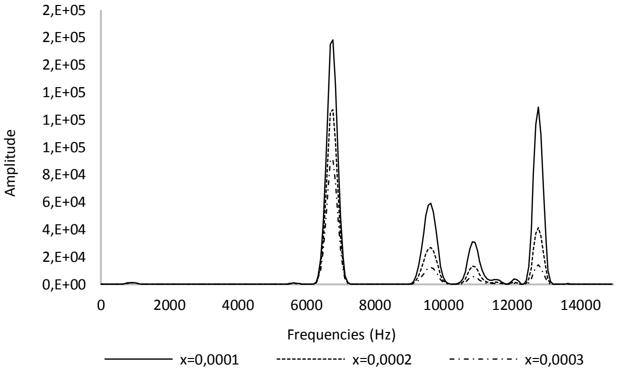


Figure 2. Damping effect on the *Multicross-Spectral Density*

In Figure 3 a dominant frequency appears at 14 kHz (translating a vibration mode). Three other less imposing frequency also appear on the figure. One of them could potentially be assimilated to the interface and the defect remains undetectable. A difference in the amplitudes in the frequency spectrum can also be noticed. The test with R=0.46 presents lower amplitudes as the reflected portion of the wave is less important than the test with R=0.71.

Table 4. Summary of the selected tests

Tests / Factors	Test 1	Test 5
R	**0.46**	**0.71**
e_1 **[m]**	0.25	0.25
d **[m]**	0.07	0.07
ξ	0.0001	0.0001

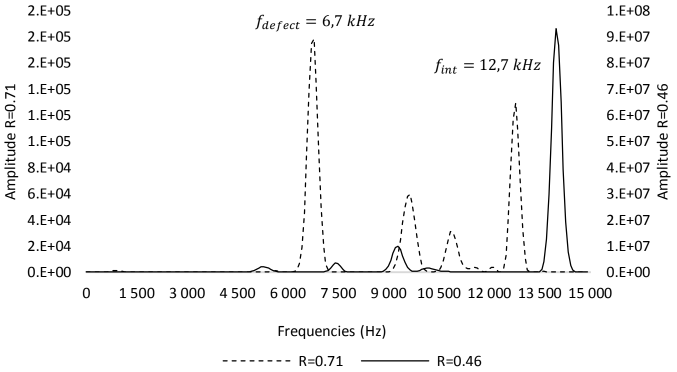


Figure 3. Reflection coefficient effect on the *Multicross-Spectral Density*

3.3 *Effect of Thickness of the first layer e_1 on the Impact-Echo response*

Two different thicknesses e_1 are considered (Table 5). In theory, we placed ourselves in a position where the detection of this latter is always possible. For $e_1 = 0.25$ m (Test 5) the thickness frequency should be 12.1 kHz and for a thickness of the first layer $e_1 = 0.375$ m (Test 6) the thickness frequency should be 8 kHz. In Figure 4, both thickness frequencies can be identified. However, a difference between the amplitudes can be noticed. Indeed, the amplitude frequencies of the numerical Test 6 are lower than numerical Test 5. This can be explained by the fact that travel time of the wave in the numerical Test 6 is longer (as the interface is deeper) so the energy dissipated is more important and therefore the reflected portion is lower.

Table 5. Summary of the selected tests

Tests / Factors	Test 5	Test 6
R	0.71	0.71
$\boldsymbol{e_1}$ **[m]**	**0.25**	**0.375**
$\boldsymbol{d}$ **[m]**	0.07	0.07
ξ	0.0001	0.0001

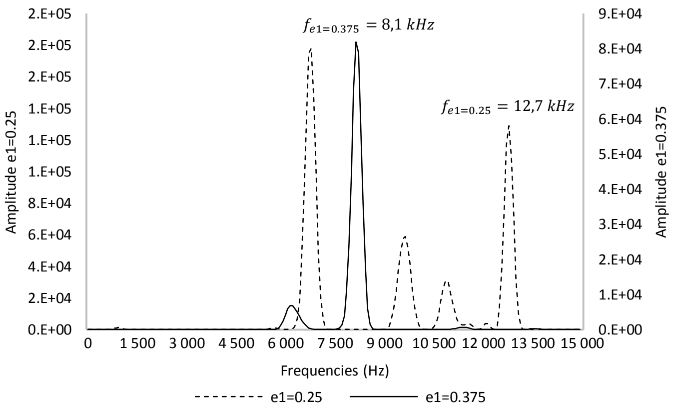


Figure 4. Thickness of the first layer effect on the *Multicross-Spectral Density*

3.4 *Effect of the Depth of the defect d on the Impact-Echo response*

Three level of depth defect are selected in this section (Table 6). As expected, the interpretation is quite complex as this factor have the greatest influence in the response. Figure 5 presents the three responses corresponding to three numerical tests with different defect depth levels. As the frequency spectrums of Test 5 (d=0.07) and Test 19 (d=0.0875) present multiple frequency pics, the numerical Test 7 with the higher defect depth presents only one dominate frequency at 11.2 kHz. This may be explained by the fact that the defect is positioned too far and only the interface is detectable. The thickness frequency appears to be 11.2 kHz which represents a result with 7% deviation in the estimation of the interface (calculated value is 12.1 kHz for the numerical Test 7). If we consider that because the defect is not detectable and the second layer is far more flexible than the first one, the latter will be free to vibrate as a simple plate. For this matter, a different shape factor β must be introduced. Gibson et al. (2015) in a recent study, stated that the shape factor depends on the Poisson's ratio as well as the shape itself. As the Poisson's ratio in their study varies from 0.15 to 0.25, the shape factor β varies from 0.96 to 0.942, opposed to a single value for solid materials β = 0.96 proposed by Sansalone et al. (1986). In the present study, the Poisson's coefficient is 0.3 so a shape factor equal to 0.942 will be considered. With this value the thickness frequency becomes 11.4 kHz which could accurately represent the thickness of the first layer.

Table 6. Summary of the selected tests

Tests / Factors	Test 5	Test 19	Test 7
R	0.71	0.71	0.71
$\boldsymbol{e_1}$ **[m]**	0.25	0.25	0.25
$\boldsymbol{d}$ **[m]**	**0.07**	**0.0875**	**0.105**
ξ	0.0001	0.0001	0.0001

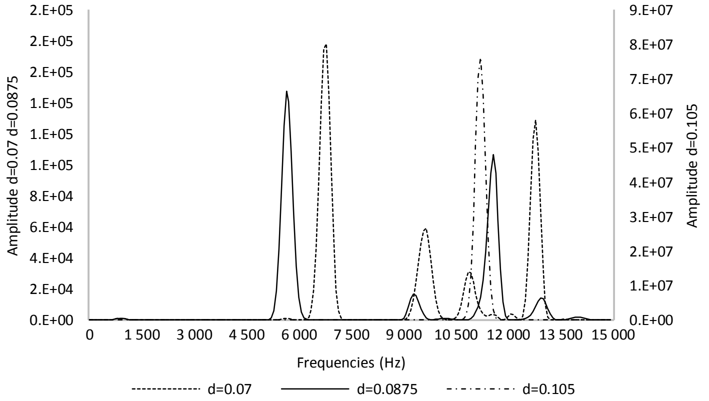


Figure 5. Depth of the defect effect on the *Multicross-Spectral Density*

4 CONCLUSION AND PERSPECTIVES

Previous studies have mainly been focusing on the localization of detect located in a single layer plate and the quality bond between the layers of bilayer plates. The identification of defects located in the second layer of a bilayer plate has yet to be explored. For this type of configuration, an appropriate signal processing and interpretation are a crucial to facilitate the interpretation. As the Impact-Echo relays primly on locating dominant frequency in the frequency spectrum, for a bilayer medium containing a defect, the interpretations by reading the frequency spectrum alone is quite complex and the necessity to introduce new reading parameters other than the frequency of the peak becomes necessary. For this matter a numerical design of experiments is being developed. The aim is to study in a first place the interaction between the input variables, and then to introduce new output variables other than the frequency peak position in order to expand the approach for interpreting the response of an Impact-Echo test. Among the four factors, only the damping coefficient seems not to affect the interpretation of an Impact-Echo test. However, the three other factors have influence on the readings. More detailed numerical design of experiments results will be presented in future work.

5 REFERENCES

Azari, H., Nazarian, S., and Yuan, D. (2014). Assessing sensitivity of impact echo and ultrasonic surface waves methods for nondestructive evaluation of concrete structures. *Constr. Build. Mater.* 71, 384–391.

Bell (2004). European railway bridge demography. Eur. FP *6.*

Bitri, A., Perrin, J., and Beauce, A. (1996). La sismique réflexion haute résolution: principes et applications.

Chaudhary, M.T.A. (2013). Effectiveness of Impact Echo testing in detecting flaws in prestressed concrete slabs. *Constr. Build. Mater.* 47, 753–759.

Gibson, A., Popovics, J.S., and ASCE, M. (2015). Lamb Wave Basis for Impact-Echo Method Analysis, *Journal of Engineering Mechanics*, 131, 438-443.

Harris, J. (1978). On then Use of Windows for Harmonic Analysis with the Discrete Fourier Transform, Proceeding in the IEEE, 66, 51-83.

Huang, Y.-H., Ni, S.-H., Lo, K.-F., and Charng, J.-J. (2010). Assessment of identifiable defect size in a drilled shaft using sonic echo method: *Numerical simulation. Comput. Geotech*. 37, 757–768.

Martin, J., Hardy, M.S., Usmani, A.S., and Forde, M.C. (1998). Accuracy of NDE in bridge assessment. *Eng. Struct.* 20, 979–984.

McCann, D.M., and Forde, M.C. (2001). Review of NDT methods in the assessment of concrete and masonry structures. *Ndt E Int*. 34, 71–84.

Medina, R., and Garrido, M. (2007). Improving impact-echo method by using cross-spectral density. *J. Sound Vib*. 304, 769–778.

Pradhan, T. (2014). Finite Element Modeling of Impact-Generated Stress Wave Propagation in Concrete Plates for Non-Destructive Evaluation. *Lehigh University.*

Proske, D., and Gelder, P. (2009). Safety of historical stone arch bridges, *Berlin, Heidelberg: Springer Berlin Heidelberg.*

Sadri, A. (2003). Application of impact-echo technique in diagnoses and repair of stone masonry structures. *NDT E Int.* 36, 195–202.

Sangoju, B., Murthy, S.G.N., Parthasarthy, S., Wiggenhauser, H., Ravisankar, K., Iyer, N.R., and Lakshmanan, N. (2009). Reliability of the Impact-Echo Method on Thickness Measurement of Concrete Elements. *NDTCE 2009, Nantes, France.*

Sansalone, M., and Carino, J.N. (1986). Impact-Echo: A Method for FlawDetection in Concrete Using Transient Stress Waves.

Sansalone, M., and Streett, W. (1997). Impact-Echo : Non destructive Evaluation of Concrete and Masonery, *NEW YORK: Cayuga Press.*

Serón, F.J., Sanz, F.J., Kindelán, M., and Badal, J.I. (1990). Finite-element method for elastic wave propagation. *Commun. Appl. Numer. Methods* 6, 359–368.

Topping, B.H.V., and Wong, F.L. (1991). Finite element modelling of the sonic method of testing masonry structures. *Comput. Struct.* 41, 109–136.