Wave Propagation Based Assessment of Cylindrical Concrete Structural Elements

Giovanni PASCALE, Camilla COLLA, DISTART Department, University of Bologna, Italy

Abstract. In structural engineering, the risk assessment of existing structures subjected to seismic action or other severe load conditions requires a complete knowledge of their health state and possible presence of damage and/or defects. Surveys based on low frequency ultrasonic waves are currently carried out for assessing concrete structural elements, aimed both at estimating the material mechanical properties and detecting defects such as voids, in-homogeneity and cracks. The transmission technique is usually adopted in ultrasonics. The evaluation of the recorded data is based on the analysis of important variations both of apparent wave propagation velocity and signal attenuation.

Nonetheless, the ultrasonic pulse method presents some limitations in dealing with in-homogeneous materials and in adopting the reflection technique because of signal scattering and attenuation. In order to overcome these application difficulties, the sonic techniques can be adopted, such as the pulse-echo and the impact-echo methods. The latter adopts a high-energy signal and operates by multiple reflection of the propagating wave, analysing then the spectrum of the recorded signal.

An experimental research program has been implemented, based on both the ultrasonic pulse and the impact-echo techniques, aimed at evaluating structural elements and at comparing the ability of both techniques in detecting and sizing defects. The testing has included laboratory concrete and masonry specimens containing artificial defects.

Nowadays, the two techniques can relay on a long experience with a variety of test cases. Nevertheless, few are the applications on structural elements with circular section. The on-going laboratory work has shown that, especially with impact-echo, the response from cylindrical elements may vary considerably from that obtained on slab-type elements.

The research results presented in this paper compare the testing procedure and outcome from ultrasonics and impact-echo on a concrete cylindrical specimen.

1. Introduction

The vast majority of structures and buildings in European Countries, a well as around the world, consists nowadays of concrete and masonry structures. These are often affected by damage due to ageing, environmental agents, overloading, vibrations and other causes. A great variety of damage situations can occur, as micro cracking and cracking due to material and structural damage, material discontinuity, and surface degradation. In addition, there is a lack of knowledge of the material properties, wall construction technique, thickness and geometry variation, consistency of the structural element, bonding between layers, inclusions such as hidden voids and other in-homogeneities, presence of defects either deep in the section or superficial. To gain information related to the above described problematic it is necessary in view of structural safety check and of the appropriate choice of material and repair techniques.

Experimental modal analysis (EMA) techniques and dynamic system identification may provide overall information about the health state of a structure but their application to cultural heritage has to be particularly careful due to the complexity of structural configuration. Furthermore it is not always possible to achieve detailed or local information by the application of these methods.

Non destructive testing (NDT) techniques are thus required in order to avoid invasive investigations and because they are more suitable for local damage detection and evaluation of single structural elements. Concrete is rarely homogeneous and, due to construction faults or other needs, it may often present defects and inner in-homogeneities. Therefore, an appropriate diagnosis of the structure may not leave out of consideration both a deep knowledge of its materials and geometric-construction information on the single structural elements.

These aims may be achieved by the application on site of some categories of NDT techniques, if the application procedures, the level and extension of the application, the testing aims and possible use of the results are well clear to the user or to the subject responsible of the investigations. The information gained by this experimental evaluation may also be used as input calibration information into analytical models [1], [2] properly applied for structural safety, and in discriminating the choice of intervention techniques. Further, these methods are applicable to assess the effectiveness of repair techniques and for long term monitoring. The first applications of NDT techniques, either single or, more often, as a combination of two or more, to Cultural Heritage on site dates back to about 20 years ago, but it is in the last decade that their use has become more extended and consolidated, thanks to a better comprehension of testing procedures and capabilities. Numerous are the applications to historic concrete and masonry infrastructures, churches, towers, bell-towers, monumental buildings as well as to historic centres and single historic residential and rural buildings [3-16]. The relationship between NDT results and local mechanical properties of the materials is also an aspect under study [17].

2. Elastic Wave Propagation Methods

Between the possible NDT techniques and methods which detect and relate the physical properties of the wall and its materials with the integrity, load carrying capacity, geometry and characteristics of the section are the methods based on the propagation of elastic waves. They provide an overall qualitative response of the masonry and concrete thanks to the propagation characteristics of acoustical waves that cross the materials. In addition, in the appropriate conditions they may deliver detailed information related to the masonry texture and concrete, the depth of discontinuities and the location and size of defects and inner features.

The most widely used of these NDT techniques exploit pulse velocity and attenuation measurements of the signal in the ultrasonic field or at lower frequency ranges. Ultrasonics in particular is very effective when analysing dense materials and small or medium size elements such as concrete ones. Methods using lower frequency waves and based on elastic shock excitation - thus employing higher transmission energy - are more suitable for highly absorptive materials such as thick concrete elements and masonry sections. Conventional ultrasonic and sonic techniques operate in transmission or single reflection of the signal, with the receiving transducer positioned in different configurations with relation to the input point. Contrary to these, another sonic method, the impact-echo method, operates by multiple reflection of the signal and the data analysis is carried out in the frequency domain instead of the time domain. Together these methods have achieved a number of goals in the investigation of concrete and masonry, also thanks to recent developments and applications [13,15].

Nevertheless, performing measurement campaigns and subsequent analysis of the results is often still difficult, depending on environmental constraints, site limitations and due to the un-homogeneity and/or anisotropy of the materials involved. The strong absorption characteristics of masonry materials and the considerable thickness of the layers represent often the greatest limitation.

3. Fundamentals of Wave Propagation

Theory of wave propagation in solids allows estimating capabilities and limitations of these techniques, according to the testing aims and site conditions. From the generation point, the signal propagates as superficial wave as well as longitudinal and shear waves along semi-spherical wavefronts in the material semi-space. The longitudinal waves present maximum amplitude in the direction of impact and their energy dominates that of shear waves. For this reason, propagation and reflection of these waves – faster than shear ones – is generally preferred in wave techniques.

Wave reflection happens at layer interface with sufficient acoustic impedance and dimensions in relation to signal wavelength, such as at external surfaces and/or internal targets: $z = \rho \cdot C_P$ where z is the impedance, ρ the material density and C_P the wave velocity. The wave propagation velocity is a function of the material density and of its mechanical properties; in particular, $C_P = \sqrt{E/\rho}$ where E is the elasticity modulus of the material. Further, $C_P = f \cdot \lambda$ that is the minimal signal wavelength λ is inversely proportional to the maximum frequency of the generated wave.

Hence, with increasing frequency, the wavelength decreases, thus improving data resolution. It follows that the resolution of the smallest recognisable feature is directly related to the dominant wavelength of the employed wave, besides the size and geometry of the tested element. Nevertheless, the wave frequency content determines also the propagation distance of the wave in the material. In fact, if high frequency components – those with small wavelengths – are suitable for locating small or superficial features, they are characterised by less energy and greater attenuation due to absorption and scattering in the masonry and concrete. The rate of attenuation is directly proportional to the frequency increase, limiting the thickness of wall section that can be tested. Nonetheless, if the wave contains sufficiently small wavelengths, a defect or other anomaly can be located depending on its lateral dimensions and depth [18]. Therefore, wave attenuation and resolution are two important limiting parameters of the wave techniques. From those it depends the choice of signal frequency to be used on site, according to the testing aims and conditions.

4. Ultrasonics

The generation of a train of ultrasonic impulses is carried out by an ultrasonic transmitter generally operating at frequencies around 50 kHz. This corresponds to approximate wavelengths in concrete of about 10 cm, longer in masonry. The ultrasonic signal, after crossing the material, is picked up by the receiving unit, which is usually positioned on the opposite side of the wall, either exactly opposite the input position or at some angled distance. Alternatively, the receiver may be placed on the same surface as the transmitter, adjacent to it or at some distance away. In order to favour the passage of the wave from the transducers to the material and vice-versa, these are coupled to the surface of the wall under investigation with the aid of coupling agents (in form of semi-liquid or gel material) which have the task of reducing the air voids at the interface. The instrumentation allows reading the time of arrival of the signal between in and out points from which the signal propagation velocity in the material may be calculated by knowing the relative distance of the in and out positions. The velocity is characteristic of each masonry type, therefore the technique has to be calibrated on site before giving start to the tests. From the attenuation of the signal in dB – information provided by the instrumentation - it is possible to calculate the absorption of the materials. The number of collected measurements depends on the aims of the tests. If a punctual estimate of the signal velocity in the material is to be achieved, the average of some readings may be sufficient, but if the testing aim is, for example, an estimate of the inner configuration of the wall or the damage detection, a much higher number of readings may be necessary.

Transducers have recently been commercialised, which do not need a coupling agent – with evident advantages in the case of application to decorated surfaces - and they are made in form of arrays of transceivers which work switching automatically from transmitting to receiving station so that a greater quantity of data can be collected at single positions and 2-D ultrasonic images of the investigated element can be produced. In addition, these new transducers are focused, so that a higher resolution can be achieved.

The limitations in signal attenuation of ultrasonic waves make the sonic tests more appealing for masonry.

5. Sonics

Pulse velocity tests are based on the generation of sonic impulses in the form of an elastic wave at a point on the structural element surface. This wave is obtained by a percussion device, generally a medium size instrumented hammer. The hammer tips are usually interchangeable to fit the different site conditions and to adapt to the material surface stiffness and roughness. A smaller or stiffer tip would produce a higher frequency wave. Adopted input frequencies in the case of sonic tests are around 5 kHz or lower. These low frequencies are ideal for crossing considerable masonry and concrete thickness, although their large wavelengths are to the detriment of resolution. Once the signal has crossed the material, it is picked up by a receiver which can be a displacement transducer or an accelerometer. Usually a coupling agent at the contact of this transducer to the surface is not necessary. As in the case of ultrasonics, the receiver may be placed in different positions with respect to the input point, according to the testing methodology. The data provided by the measurements consists once again in the peak time of the wave between in and out points. The amplitude of the received signal is usually an additional information.

6. Impact-echo

The impact-echo method is a sonic technique which makes use of the multiple reflection of low frequency waves (usually below 50 kHz) in the section of material. These are excited by a short, elastic, mechanical event obtained via tapping a small hammer or metal sphere on the testing surface. The receiving transducer can be a displacement transducer or an accelerometer. It is located adjacent to the impact point and it measures the wave reflections (or echoes) after the impact. The train of wave echoes produces transient resonances in the section of the structural element, whose frequencies depend on the element geometry and material characteristics [18]. This signal is recorded as a waveform in a time window of a few milliseconds. Through a Fast Fourier Transform, the time domain signal is transformed in a frequency spectrum which highlights the frequency components and amplitudes.

Analysis of the registered waveforms takes then place in the frequency domain, where the predominant signal frequencies appear as peaks. The measured transient resonance frequencies serve to calculate the section thickness and the depth of any internal feature. The frequencies registered in the spectra are used to determine the geometric dimensions of the section and its integrity or to evaluate position and dimension of present defects thanks to the relation between v_p, the wave propagation velocity, f, the measured frequency, e d, the depth of the defect or the element thickness: $d = \frac{v_p}{2 \cdot f}$ The peaks' position, amplitude and shape are useful parameters to evaluate the structural integrity of the tested element. An important discriminating criterion between the peaks on the spectrum is their amplitude. This parameter can be largely influenced by the frequency content of the wave, consequently it is necessary to carefully select the impact source [19].

7. Testing of Bar-like Elements with Circular Section

From the view point of impact-echo testing, bar-like structural elements such as beams, columns and pillars produce a different kind of response if compared with plate-like elements. In the case of plates and walls subjected to impact-echo testing, the dominant vibration mode is that of the plate thickness (fig. 1a,b,c) due to the multiple reflections of the compression wave between top and bottom external surfaces of the element. The impact-echo response is dominated by the presence of a high-amplitude peak in the spectrum (fig. 1d). whose frequency allows estimating or calculating (if the wave speed in the material is known) the thickness of the element.

Different is the case of structural elements with bounded cross-section, such as circular and square section, where the impact response may be much more complex. The multiple wave reflections within the cross-section plane – orthogonal to the main axis of the element – excite a number of additional vibration modes, whose resonance frequencies dominate by amplitude the thickness frequency in the spectrum. Fig. 2 shows the shape of the first six cross-sectional vibration modes, typical of elements with solid circular cross-section [18]. The response measured at any point along the perimeter of a transversal section is the superposition of the displacements caused by all vibration modes – including flexural, torsional, longitudinal - but cross-sectional modes are dominant. Each is visible in the registered spectrum thanks to a specific peak. The number of visible peaks is influenced by the mass of the impact, i.e. the duration of impact, thus by the frequency content of the signal employed. In bar-like elements, the impact-echo response of each cross-sectional geometry – square, circular, etc. - is distinctive. The frequency of the fundamental or first cross-sectional mode of vibration, f_1, for the case of circular cross-section is given by [18]:

$f_1 = \frac{0{,}92 \cdot v_p}{2 \cdot D}$ where v_p is the compression wave speed and D is the length of the diameter of the circle.

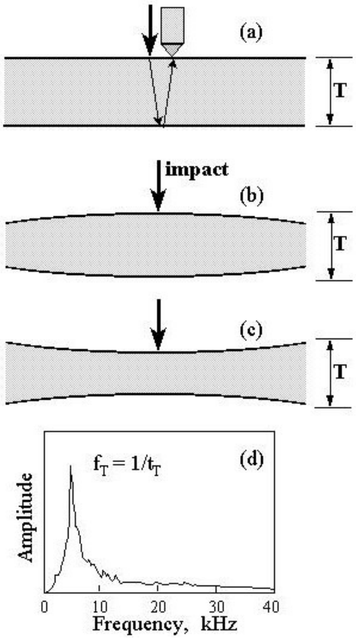

Figure 1. – Impact-echo testing on slab element [18].

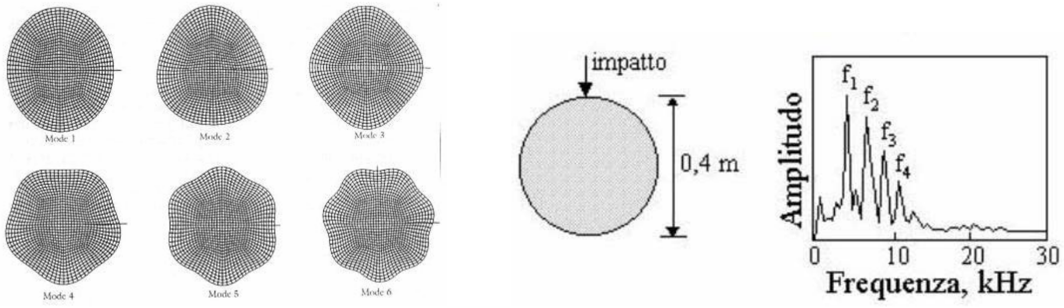

Figure 2. - Cross-section vibration modes and spectrum from testing on circular element [18].

8. Specimen Description

In order to evaluate the influence of different kinds of damage, a concrete specimen was cast in the laboratory and contained some artificial defects, such as voids and cavities. It is a 0.81 m high cylinder, 0.305 m in diameter. It presents 5 defects, of which the top one is a large cylindrical trough, 0.18 m in diameter. At a lower position, in the middle of the specimen, is a large prismatic defect (dimensions of 0.1 x 0.1 x 0.2 m high) at approximately 0.1 m depth from the lateral surface. Other defects have smaller prismatic shape, whilst a last one is in form of a horizontal polystyrene sheet.

9. Instrumental Apparatus

9.1. Ultrasonic Equipment

A microseismic analyser SICEC HPFG 4 was used in combination with piezoelectric transducers operating at 70 kHz frequency. The analyser is provided of operator-adjustable pulse repetition rate as well as amplification of the received signal and CRT for continual display of time function vibrations.

9.2. Impact-echo Equipment

Impact devices in the form of small steel spheres were used in impact-echo testing in combination with a ICP accelerometer operating up to 60 kHz frequencies and a signal amplifier. The PC for data recording was supplied with a 1-GHz data acquisition card and software. The software used for data handling and visualisation is a widely diffused software, in-house adapted for impact-echo measurements. This software allows visualising on the computer screen both the single signal waveforms and their spectrum. It also builds in real time as the measurements proceed a 2-dimensional pseudo image of the tested element.

10. Experimental Procedure and Results

10.1. Ultrasonic Tests on Cylindrical Specimen

A number of horizontal sections were marked on the specimen height. Each section was scanned by means of measurements along different crossing paths via the through-transmission method. In the case a defect was suspected or detected, a more detailed investigation was then carried out. In this case, measures along standard paths – diameters and a few chords - were followed by a dense mesh of local measures. Once a fault was detected on a section, additional measures were collected at higher and lower positions in order to delimit its size. The data analysis was based on variations of both pulse velocity and signal attenuation values from expected ones. In fact, both parameters are sensitive to damage states, even though in different ways: the attenuation is more sensitive to wide cracks, whereas pulse velocity is largely affected by damaged areas. Both velocity and attenuation are affected by large voids.

Fig. 3 shows the results from all studied sections. The estimated defects are very similar to the real ones present in the same section. The analysis takes into account variations of wave speed, attenuation values or both. The defects were detected with good accuracy, for what concerns shape, dimensions and location. These are very similar to the real defects.

10.2. Impact-echo Tests on Cylindrical Specimen

The scanning impact-echo technique [10] was applied, that is readings were collected along measurement lines with equally spaced stations. In particular, measurements were collected in the vertical and horizontal – along the circumference perimeter - testing direction, in order to produce 2-D images of the specimen sections. Due to the small dimensions of the specimen and to the closeness and multitude of artificial defects in it, the single stations were densely spaced. The experimental procedure consisted in coupling the transducer to the surface and in keeping it in position while an impact was provoked beside the transducer, by tapping a ball bearing on the concrete surface. If a signal of sufficient quality was visualised on the computer screen, it was saved on the storage disk. The impact and receiving devices were then moved on to the next reading station along the measurement line, where data collection progressed.

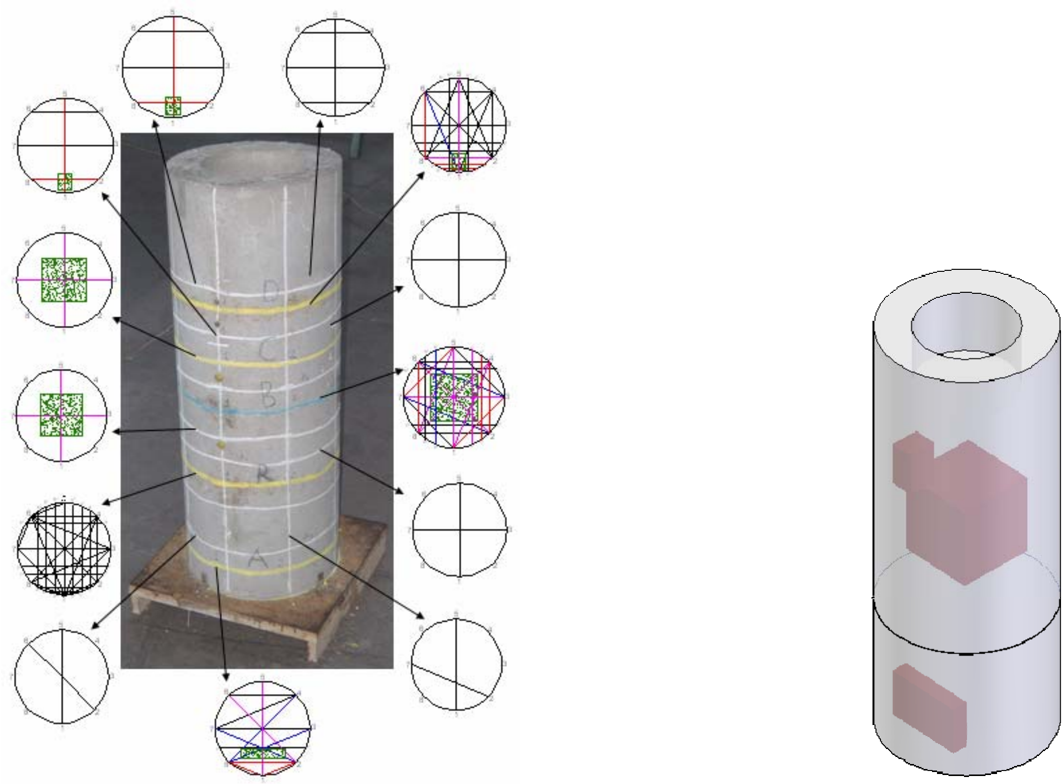

Fig. 3 - Ultrasonic analysis of all sections of the cylindrical specimen (left side) and specimen's reconstructed inner geometry (right side).

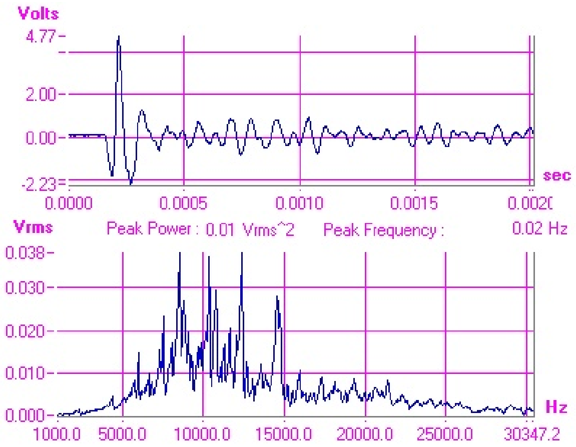

Fig. 4 - Spectrum of a solid cylindrical portion.

The wave propagation velocity in the specimen was estimated around 4200 m/sec and the signal minimal wavelength approximated 0.1-0.13 m, that is approximately double than the employed ultrasonic' signal wavelength. The technique was able of correctly locate some of these defects.

In the impactechograms the resonant frequencies due to cross-sectional vibration modes described above are visible as faint parallel lines at distinctive frequencies. Where defects are present in the specimen' section, these frequencies shift towards lower frequencies testifying the reduction in section stiffness. This observation is a good indicator of the presence of a cavity in the section. As an example, a single spectrum registered in a position where the specimen' section is solid is shown in fig. 4 where peaks due to transversal cross-sectional vibration modes are evident at frequencies of 6, 7.58, 8.49, 10.35, 12.35 e 14.55 kHz.

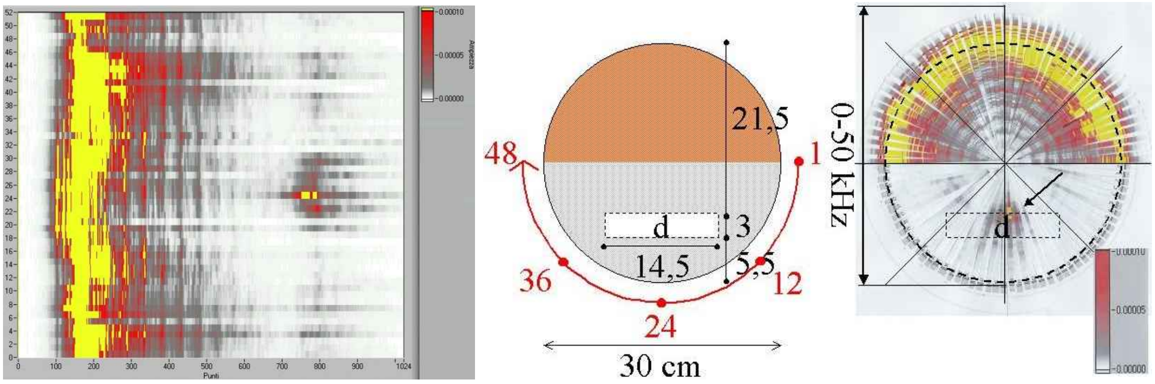

Fig. 5 - Impactechogram at a horizontal section at 7 cm from the bottom edge of the specimen (left); measurements position and reconstructed geometry of the section (right side).

An example of unfiltered impact-echo data collected along a horizontal line at 7 cm from the bottom edge of the specimen is shown in fig. 5, representing a specimen cross section. The data were collected along a semi-circular line. In this image are very evident the cross sectional vibration modes, appearing as grey vertical lines. The specimen's thickness frequency - the yellow vertical line - shows lower frequency around the mid of the measurement line, where the measurement stations are closer to the defect "d" which influences the wave propagation path and the section stiffness. Between stations 20 and 32, a high frequency reflection appears at circa 38 kHz as a grey, red and yellow spot, representing the defect "d". Note that this time the defect appears smaller than its real length (14.5 cm) because, at the side stations, the wave does not propagate perpendicular to the surface of the defect and, most of the wave being diffracted, it cannot reach the receiver position. Fig. 5 right is the reconstructed frequency cross-section of the specimen. The data are superimposed to real geometric dimension of the concrete column and compare well with it. For a better geometric correlation, a visualisation of the reconstructed depth cross-section of the specimen may also be performed.

11. Conclusions

The paper has analysed the ability of two different non-destructive wave propagation methods - ultrasonics and impact-echo - in gaining evaluation information relative to structural elements. It has shown the capability of detecting defects in the form of voids in view of the diagnosis and conservation of concrete structures. The analysis carried out with ultrasonic testing allowed detecting the simulated defects with good accuracy except for some small defects which were not located. Results from impact-echo testing showed the sensitivity of the technique to the depth and lateral location of defects. Novel experimental work has been carried out via bi-dimensional impact-echo on a bar-like concrete element with circular cross section. An example of image editing was performed on an impactechogram in order to reconstruct the geometry of investigated circular cross-section. Such images become directly comparable with the specimen's sections and quantitative information extracted from the data may be related to the real element conditions. The location of defects may be visually spotted on the images and the depth and lateral extension of any inhomogeneity may be evaluated. It is important to stress that each technique requires good user knowledge and preliminary calibration on site.

12. Acknowledgements

The authors are grateful to the staff of the LaRM, Materials Testing Laboratory of DISTART, University of Bologna for their efforts during the experimental program. The graduate students Alessio Giammarruto and Luca Mengoli are acknowledged for their help in performing the experimental program.

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