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Analyzing two different data processing strategies for monitoring concrete structures using ultrasonic pulse velocity

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ABSTRACT

The increasing number of early deterioration symptoms found in relatively new concrete structures provides a strong argument for the development and validation of techniques to monitor the condition state of concrete elements and provide data to estimate the potential service life. The use of NDT monitoring techniques is an important way to prevent and control the deterioration of concrete structures without damaging the material. Ultrasonic Pulse Velocity (UPV) measurements seem to be a quite effective way to perform quality control, since this reliable and flexible test method allows an in-depth analysis of the material's condition. Using UPV data it is possible to check the concrete uniformity, accompany the deterioration, detect internal flaws and voids and, by means of a comparison with reference specimens, even estimate the compressive strength. The results indicate that surface mapping seems to be a better way to analyze and visualize UPV results.

Keywords: concrete; ultrasonic methods; surface mapping; statistical analysis.

RESUMO

O crescente aumento dos sintomas de deterioração precoce em estruturas de concreto serve de argumento para o desenvolvimento e validação de técnicas de monitoramento do estado de conservação das mesmas. Além disto, fornecerem dados para estimar a vida útil das estruturas. A utilização de Ensaios Não Destrutivos permite a prevenção e o controle da deterioração de estruturas de concreto, sem danificar o material. O ensaio de Velocidade de Propagação do Pulso Ultrassônico (VPU) é uma forma bastante eficaz para realizar o controle de qualidade. Utilizando os resultados do ensaio de VPU é possível verificar a uniformidade de concreto, acompanhar sua deterioração, detectar falhas e vazios internos e, por meio de uma comparação com as amostras de referência, até mesmo estimar a resistência à compressão. Os resultados obtidos neste trabalho indicam que através do mapeamento superficial consegue-se analisar e visualizar os resultados dos ensaios de VPU.

Palavra-Chave: concreto; ultrassom; mapeamento superficial; análise estatística.

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1. INTRODUCTION

Nondestructive Tests (NDT) can be described as methods to examine an object, material or system without causing damage or impairing its future usefulness. By definition, NDT methods do not affect its target´s appearance or performance.
According to the ASNT (2012), NDT methods can be used to check variations in internal structure; to detect changes in surface conditions, the presence of cracks or other physical discontinuities; to measure the thickness or determine other characteristics of industrial products.
Nesvijski (2003) argues that NDT methods are especially suitable for testing materials and structures with a long service life because they allow us to evaluate them in-situ and in service, and to monitor the changes in condition state over an extended period of time. Continuous monitoring enables the early detection of problems, resulting in easier and more economic treatment and recovery alternatives.
For these reasons, the use of NDT has become a subject of interest in several countries. In Brazil, the application of these techniques is still restricted but it is growing rapidly in some sectors. Civil engineering is a field in which the interest on NDT techniques is on a rise.
In fact, over the last century, several NDT methods have evolved from ingenious benchwork tools to become indispensable tools for material´s analysis. Today, NDT methods play a very important role, for example, in the inspection procedures for some infrastructure elements, such as bridges, highways, pipelines, tunnels, and other critical civil and industrial structures. The data collected is sometimes critical for planning interventions on the aging infrastructure, with the aim of avoiding serious deterioration and reduce costs and risks (Lorenzi et al, 2004). Moreover, they do not just allow the evaluation of aged and deteriorated structures, but can also be used for quality control of new structures, Nogueira (2002).
The work described in the paper is part of a research effort carried out by the LEME/UFRGS team to evaluate the usefulness and precision of UPV measurements and to develop adequate interpretation strategies to make sense of the data obtained. In this study, the results of UPV tests carried out on a beam containing several induced defects, simulated using pieces of wood and styrofoam, were analyzed. The objective is analyses two different interpretation techniques, one based on statistical neighboring analysis and other using 3D mapping. The results indicates that the usefulness of the ultrasonic readings for defect detection may depend upon the establishment of a suitable inspection grid.

2. USING ULTRASONIC PULSE VELOCITY MEASUREMENTS IN CONCRETE

Amongst the most well known and commercially available NDT methods, the ultrasonic pulse velocity (UPV) measurements can be considered as one of the most promising for the evaluation of concrete structures. The characteristics of the method makes possible to analyze the material homogeneity, facilitating the diagnosis of defects and the control of the condition state of structures during their service life. An additional advantage is that ultrasonic testing offers the chance to make a continuous control of structure elements over time.
The results of these analyses can be used for prognostic of the quality or to correction the technological process. The ultrasound can be used for example, as the concrete quality, detect voids or evaluate zones damaged by fire.

There is a considerable challenge in evaluating an heterogeneous material such as concrete. As pointed out by Nesvijski (2001), composite materials require adequate NDT means. Concrete properties can vary considerably, depending on the nature and proportions of its constituents, the construction methods applied to create it, and the loading and environmental conditions to which it will be subjected over time.
The dynamic nature of concrete is one of the very reasons why the development of control methods to determine the condition and ascertain the quality of concrete is critical (Lorenzi, Silva Filho and Campagnolo, 2004).
As widely known, the most important control parameter used today for concrete, despite its limitations, is the compressive strength. Therefore, the possibility of estimating the concrete strength from ultrasonic readings, regardless of the uncertainties, is quite attractive. This explain why concrete is practically the only major material in which strength determination is attempted by ultrasound (Popovics, 1998).
According to some studies, it is possible to make a rough estimate of strength from ultrasonic data, especially when combined with the extraction of core samples in order to provide a reference for the analysis, as discussed by Lorenzi, Caetano and Silva Filho (2003). The strategy is to explore the relationship between the quality of concrete and the velocity of the ultrasonic pulse sent through the material. The idea is that the pulse velocity will be a function of material density and stiffness, both of which can be correlated with compressive strength.

2.1. Basics of UPV Techniques

UPV is one of the most widely used NDT methods (Lorenzi, Silva Filho and Campagnolo, 2004). The UPV method is based on the propagation of a high frequency sound wave through the material. The basic idea is to project the sound inside a material and measure the time necessary for the wave to propagate though it. If the distance is known, it is then possible to determine the average pulse velocity (ASTM, 1995). The speed of the wave will vary depending on the density of the material, allowing the estimation of the porosity and the detection of discontinuities.
The method is normally based on the use of portable equipment, composed by the source/detector unit and the surface transducers, which work in the frequency range of 25 to 60 kHz (Popovics, 1998). The quality of the transmitted pulse is important, and in a first time the best coupling of transducer with solid edge must be designed (Buyle-Bodin, Ammouche, Garciaz, 2003).
The standard methodology of UPV applications for concrete is based on the propagation of ultrasonic pulses through a specimen. If a wave encounters a crack or void, it will be diffracted around the discontinuity (Popovics, 1999). The propagation time expresses the density of the material, which might be correlated with the mechanical properties, such as the compressive strength and the modulus of elasticity (Meneghetti, Padaratz, Steil, 1999).
The readings should be adjusted, if possible, to consider the concrete age, aggregate and cement type and proportion, carbonated depth, the presence of water and the effects of other variables that might influence the relationship between the compacity and the mechanical properties, such as the dynamic moduli and the compressive strength (Nesvijski, Nesvijski, Lorenzi, 2000). The results can also be used to check uniformity, detect voids or estimate the depth of a surface crack (Qasrawi, 2000).
The evaluation of ultrasonic results is, however, a highly specialized and complex activity, which requires careful data collection and expert analysis (Lorenzi, Caetano, Silva Filho, 2005). Only by means of a throughout and well done analysis, a trustworthy diagnosis can be obtained. For example, to map the homogeneity of one structure it is necessary to interpret and connect a large number of UPV readings.

To make an adequate analysis it is necessary to have a reliable interpretation strategy. The best ways to deal with this data have not yet been established. This research investigates strategies to facilitate the analyses and how computational support might be used.

3. EXPERIMENTAL PROGRAM

In the present work two strategies, multiple comparison of averages and surface mapping, were used to interpret data from an experimental beam, 20 x 40 x 100 cm, where some defects were induced. The objective was to verify the efficiency of each of the techniques in terms of defect detection.

The experimental beam was created using concrete with mix proportions 1:2.57:3.43 (cement: fine aggregate: coarse aggregate) and a water/cement relationship w/c = 0,58. Inside the beam several objects were placed, such as Styrofoam balls and wood pieces, in order to simulate the imperfections or defects that could exist in real concrete elements. The objects used can be observed in figures 1 and 2. They were kept in place using nylon threads. Reinforcement bars were placed in half of the beam, to check if their presence would influence the UPV readings.

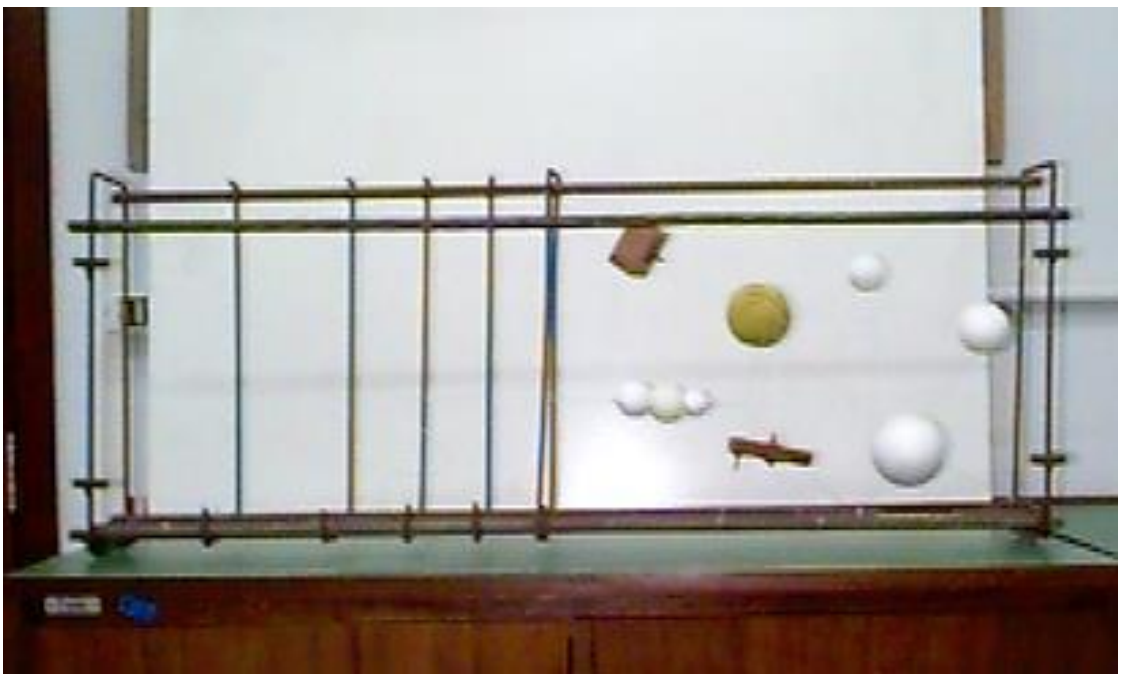

Figure 1. Detail of the reinforcement and the objects in the beam.

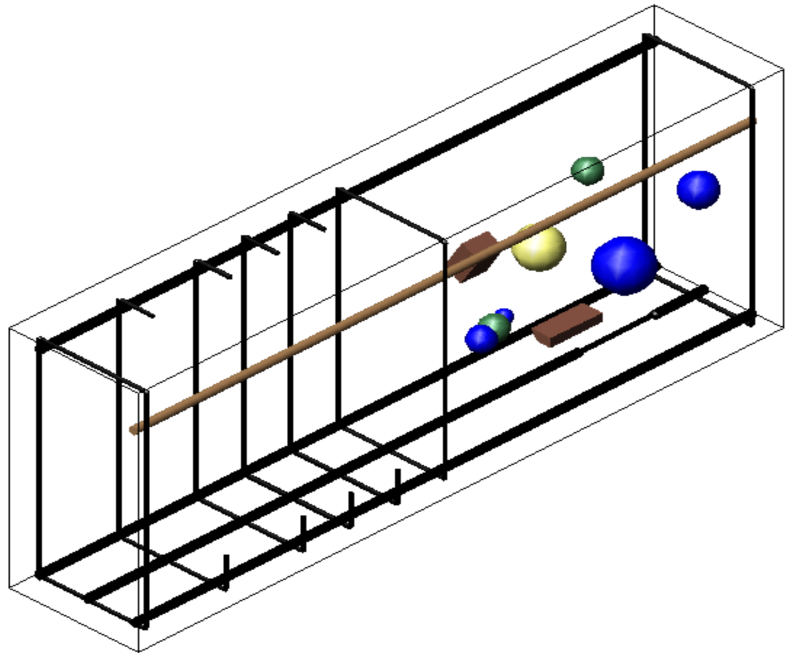

Figure 2. Simulation of defects in the beam.

The beam was tested using portable PUNDIT equipment, provided with 54 Khz transducers. According to Naik and Malhotra (1991), this frequency range was chosen to minimize the influence of concrete strength variations in the measurements. Since the objects placed inside the experimental beam varied between 30 and 95 mm, they could all potentially be detected by the equipment. Two measurement grids were used (one composed of 75x75 mm squares and the other made of 150x150mm squares), in order to verify if grid refinement would provide better results. The grids were superimposed on the lateral face of the beam, which had 100 x 40 cm. This means that the larger grid was composed by 18 dots while the smaller one was made of 55 points. Figures 3 and 4 show the measurement grids marked in one of the sides of the beam. Direct measurements through the beam and indirect measurements joining each point of the grid on each side were then taken.

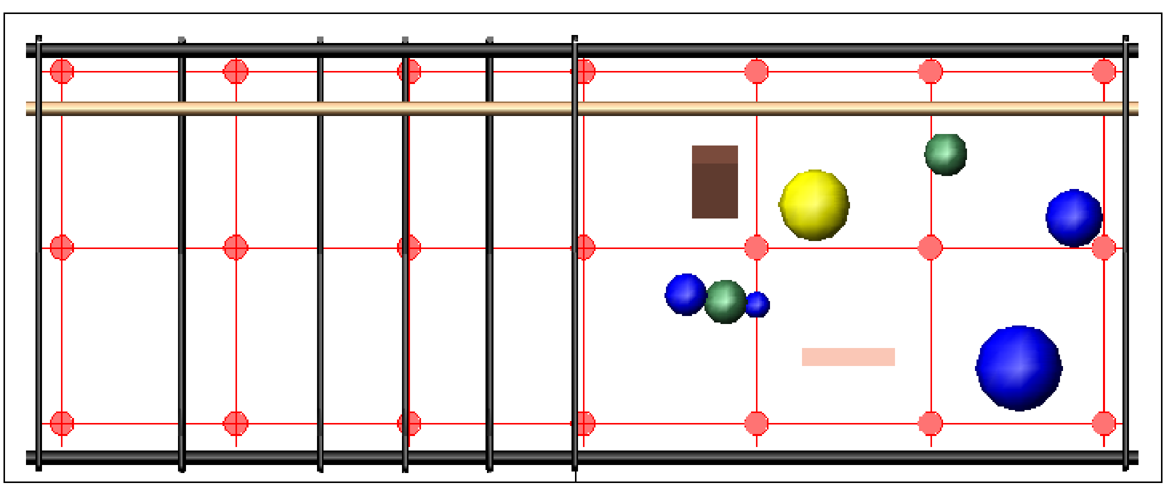

Figure 3. Disposal of objects into the beam and positioning of 150mm grid.

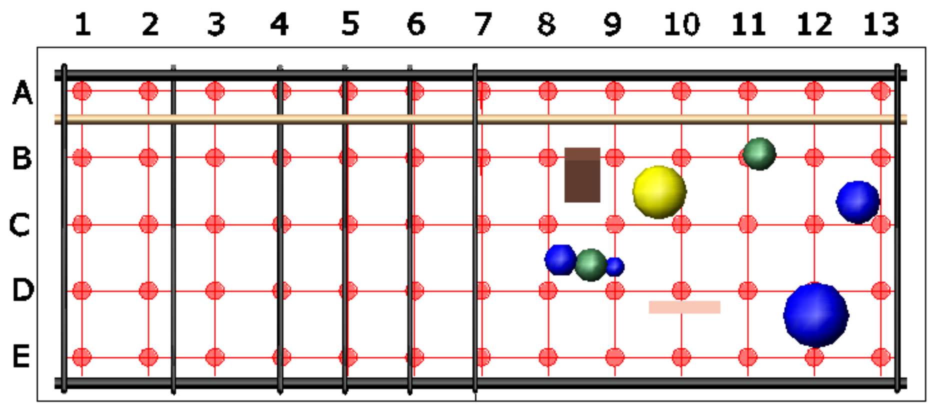

Figure 4. Disposal of objects into the beam and positioning of the 75 mm grid.

Figure 5 shows the measurements being performed. As can be noticed in the image, a positioning device was used to ensure that the transducers were properly placed.

Figure 5. View of the execution of the UPV test.

The first interpretation technique was based on the statistical concept of multiple average comparisons. Results from the 6 indirect measurements joining the 4 points that created each square of the larger grid were combined and their average and standard deviation calculated. Using an statistic Sotfware (Statistica 8.0), a comparison of the internal variation inside each square and the variations between neighboring squares was carried out, in order to determine if the squares could be considered as statistically different, which might indicate, in theory, the presence of abnormalities.

The second interpretation technique had a more graphical nature. Using a surface mapping software (Surfer 7.0), a contour map of the data was created. The coordinates for the contour map were the position in the grid (expressed as X and Y values) and the UPV measurement (which constituted the Z coordinate). Each indirect measurement was placed at the midpoint of the line connecting two points of the grid. Adequate intervals were stipulated for the UPV measurement, in order to create a color map of the pulse velocities alongside the beam.

4. ANALYSIS OF THE RESULTS

For the statistical interpretation strategy, hypotheses tests were done considering:

H_0 = Null hypothesis - the averages of the samples are equal.

H_1 = Alternative hypothesis - the averages of the samples are different.

$H_0 = t_{experimental} \leq t_{theoretically}$ - Region of acceptance of Hypothesis

$H_1 = t_{experimental} > t_{theoretically}$ - Region of rejection of Hypothesis

Figure 6 shows some of the results obtained for the grid of 150 mm. The testing of hypothesis pointed out the existence of significant differences between quadrants Q4 and Q9, Q4 and Q5, Q3 and Q9, Q2 and Q9, and Q1 and Q8, as seen in figure 6. In each figure, the quadrant filled with diagonal lines is the one taken as the reference value. The dotted squares constitute the region of acceptance (squares with averages statistically similar to the reference square) while the filled squares represent the rejection region, that is, squares that could be considered as substantially different from the reference.

Combining the results, it is possible to assume that quadrants Q8, Q9 and Q5 tend to present lower UPV values than the rest, indicating regions with lower compacity. Unfortunately, these regions did not coincide well with the position of the induced defects.

The procedure was repeated using the smaller grid, to check if the refinement would increase the sensitivity of analysis. Special attention was paid to quadrants that were highlighted as composing the rejection regions for the 150 mm grid. However, the results obtained with the smaller grid were even less clear and did not help the interpretation. For example, most significant differences pointed out occurred between quadrants Q1 and Q34, Q1 and Q43 and Q1 and Q44, positions which did not coincide with the real placement of the objects or with the results from the analysis of the larger grid.

Regarding the surface mapping results, the image contour surfaces obtained were quite interesting. Analyzing the image shown in Figures 7 and 8 it is possible to verify clearly the existence of regions where the readings are lower or higher than the average. The position of these regions had a good correlation with the position of the defects. In fact, it is quite easy to locate the region where the largest Styrofoam ball was placed. Strangely, some of the defects caused increases in UPV velocity. In any case, the effect of the disturbances is quite clear.

When direct measurements were used to create the map, however, the defects cannot be so easily located, as seen in Figure 9. In these images, hotter (red) zones indicate lower UPV values, indicative of the presence of voids or defects. Colder (blue) zones indicate higher UPV values, indicative of more compact zones (or influenced by the presence or rebar).

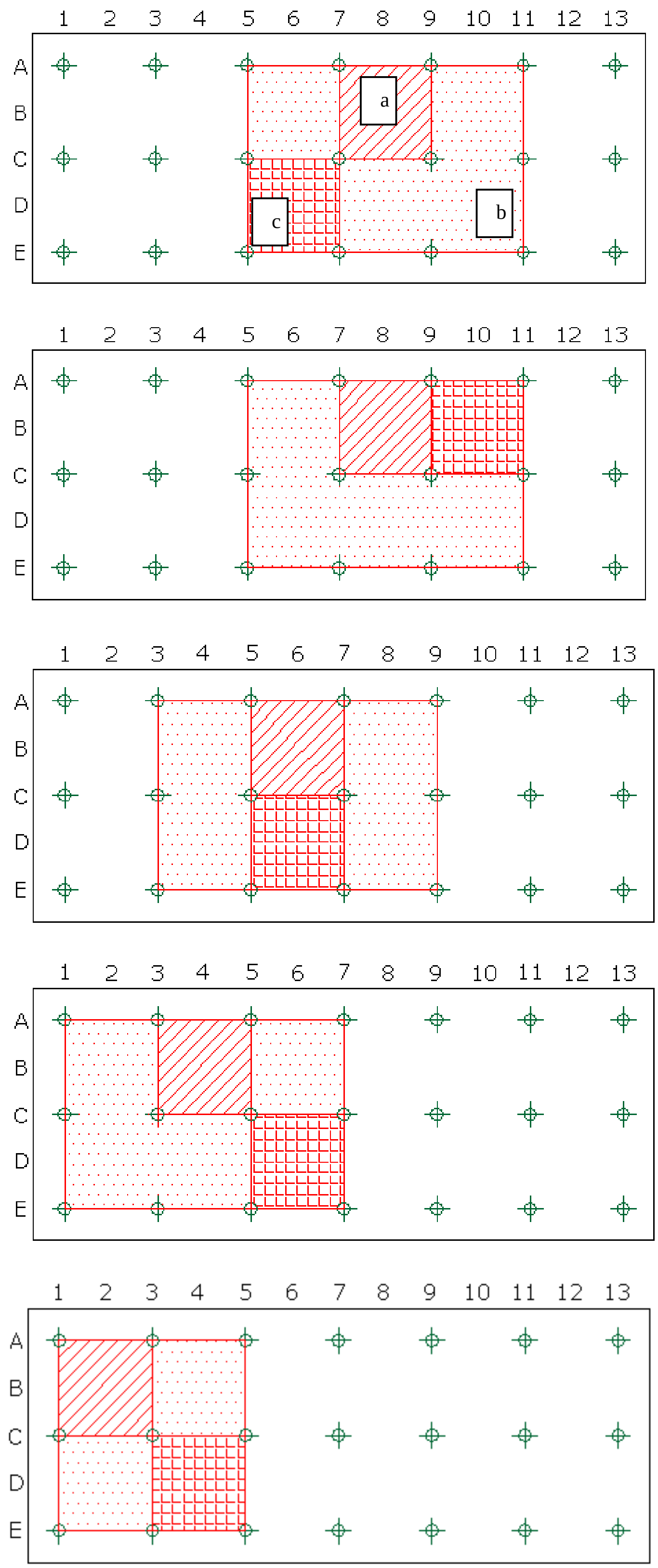

Figure 6. Results of hypotheses tests - Grid 150 X 150 mm: (a) diagonal lines - reference value, (b) dotted squares - region of acceptance, (c) filled squares – region of rejection).

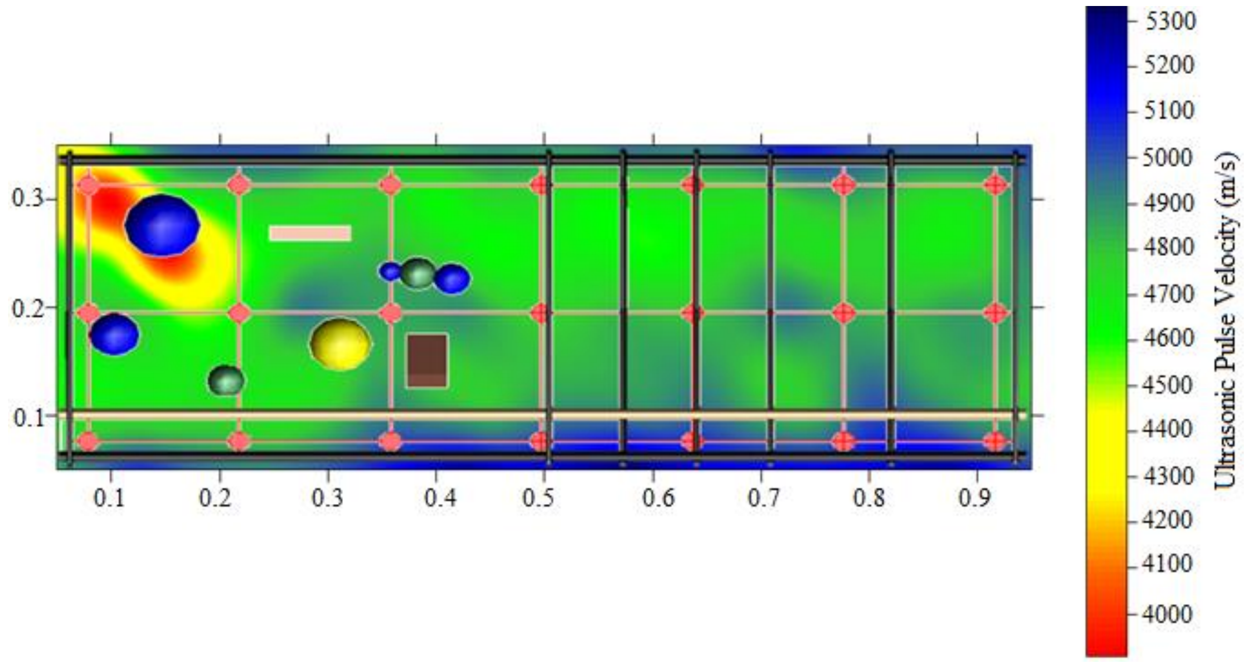

Figure 7. Surface Analysis, Indirect Readings – Face 1 – Grid 150 X 150 mm

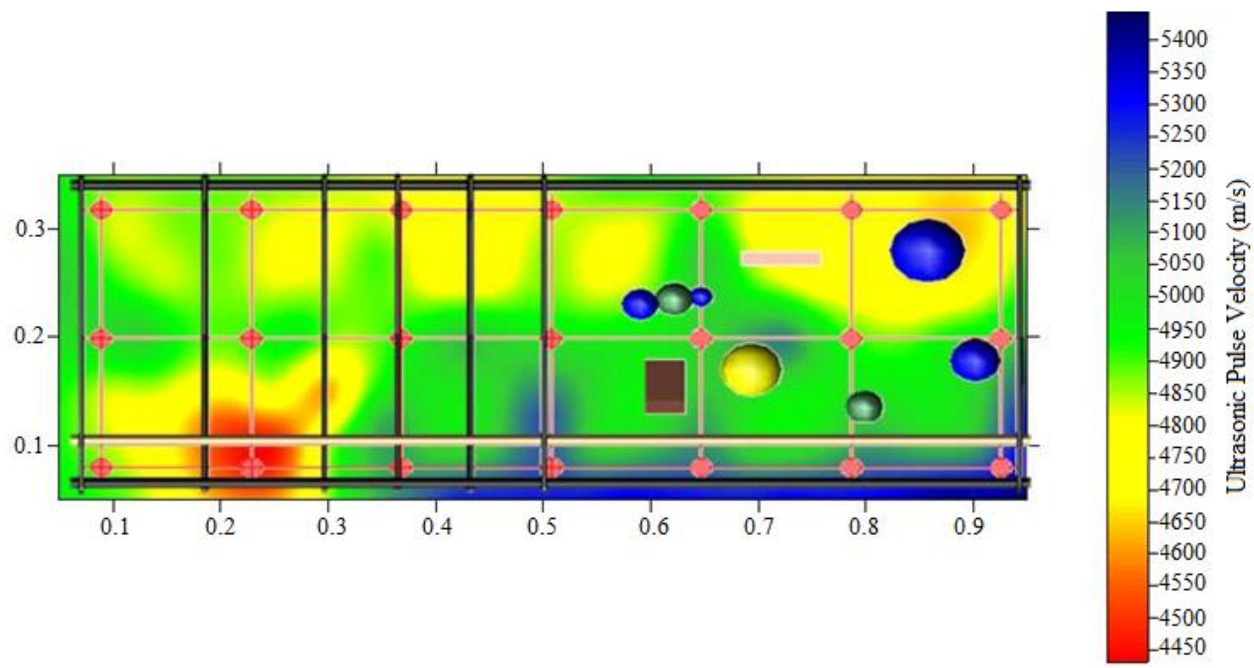

Figure 8. Surface Analysis, Indirect Readings – Face 2 – Grid 150 X 150 mm

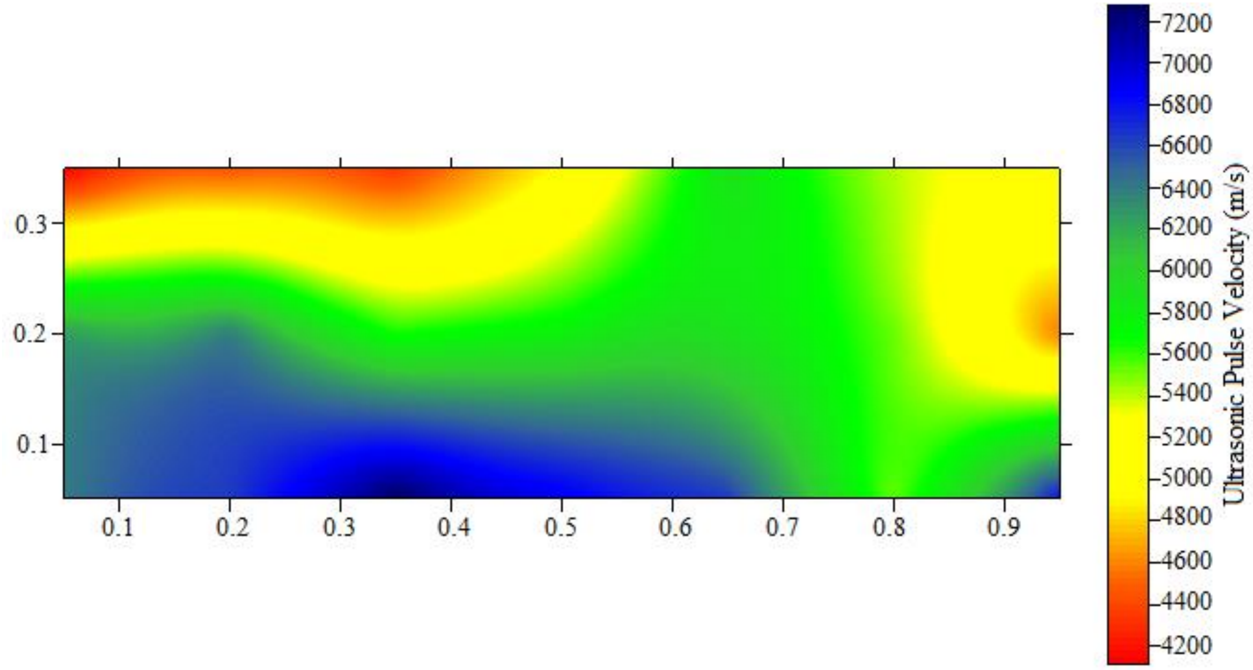

Figure 9. Surface Analysis, Direct Readings – Grid 75 X 75 mm

Despite the uncertainties, the analysis of the contour maps - similar to those that would have been produced if an investigation of a real structure was under course – indicates some trends. The presence of the wood pieces and the hollow tennis balls seems to affect more the measurements than the solid Styrofoam balls. The smaller wood piece located nearer to the top of the beam only shows itself on the face 2 image, possibly because it was closer to this side of the beam. The presence of the tennis ball is also more marked on this side, although it appears at the side A. The single table tennis ball is only noticeable on the face 1 image. The problems nearer to the bottom of the beam seem a little displaced but they appear at both sides, as 3 clear drops in UPV values.

Figure 10 shows that, similarly to what happened in the statistical analysis, when the 75x75 mm grid was used, the analysis become less clear and it was not possible anymore to detect any suspect region where the objects could be located, because of the background noise.

In order to check if the diagnosis made with the contour map images were reliable, sample cores were taken at some points chosen based solely on the contour images. Figures 11 shows some of the extracted cores, providing clear evidence to the fact that the defects could be adequately located using only the NDT data, without any prior knowledge about their position.

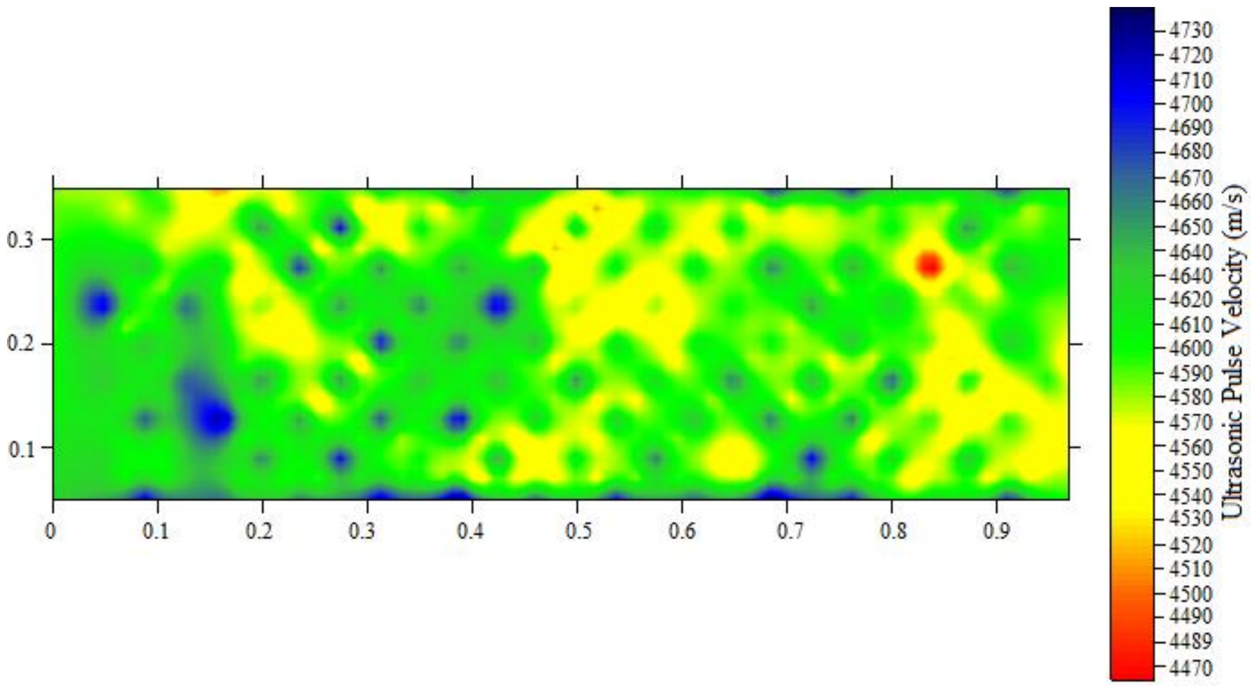

Figure 10. Surface Analysis, Indirect Readings – Face 1 – Grid 75 X 75 mm

Fig.11 Core samples showing the table tennis ball and the small piece of wood

5. CONCLUSIONS

The results obtained indicate that UPV measurements can be successfully used to detect voids in concrete elements, providing that an adequate interpretation strategy is adopted. Between the two strategies tested, image mapping showed itself as more promising and intuitive. The contour maps generated are quite easy to read and interpret. They provided a fairly good assessment of problematic regions, when the larger grid and indirect measurements were used. It was shown that indirect measurements are more useful than direct ones, for defect mapping purposes, because they tend to cross larger portions of concrete.

The question of grid size was critical. The data collected with the smaller grid was quite affected by local variations in concrete quality and surface waves, creating a background noise that cluttered both types of analysis, the statistical and the graphical one. Even for the larger grid, the statistical analysis was not able to adequately locate the defects. It gave the impression of being less sensitive and clear, not quite able of providing good results.

The combination of ultrasonic measurements with the generation of contour maps seems to be a quite effective way to map analyses the homogeneity of concrete. More tests are needed, nonetheless, to clarify the real potential of this technique for defect detection in real structures.

In short, the study indicates that ultrasonic tests can be a useful tool for structural analysis, but further studies are needed to systematize strategies for adequate data collection and define the recommended interpretation tools to be used.

6. REFERENCES

ANNUAL BOOK OF ASTM STANDARDS, ASTM E 114-95 (1995), *Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method*, Vol. 03.03 Nondestructive Testing, (West Conshohocken, USA: ASTM): 920 p., p. 12-15.

ASNT (2012). *Introduction to Nondestructive Testing*. The American Society for Nondestructive Testing. http://www.asnt.org/.

Buyle-bodin F., Ammouche A., Garciaz J. (2003), *Contribution of coupling non-destructive methods for the diagnosis of concrete structures*. in: International Symposium Non-Destructive Testing in Civil Engineering. http://www.ndt.net, Berlin: (Germany).

Lorenzi A., Silva Filho L. C. P, Campagnolo J. L., Strieder A. J., Caetano L. F. (2004), *Using Non-Destructive Testing for Monitoring Concrete Elements of Sizable Structural Members*, in: Proc. Structural Materials Technology (SMT): NDE/NDT for Highways and Bridges. Buffalo: (USA). CD-ROM.

Lorenzi A., Caetano L. F., Silva Filho L. C. P. (2003), *Redes Neurais Artificiais para Avaliação dos Resultados de Ensaios Ultrassônicos em Concreto*. in Proc. Congresso Latino-americano de Patologia das Construções. Mérida: (México). CD-ROM.

Lorenzi A., Caetano L. F., Silva Filho L. C. P. (2005), *Using Ultrasonic Pulse Velocity for Monitoring Concrete Structures*. in: Proc. The Third U.S.-Japan Symposium on Advancing Applications and Capabilities. Maui: (USA). CD-ROM.

Lorenzi A., Silva Filho L. C. P., Campagnolo J. L. (2004), *Using a Back-Propagation Algorithm to Create a Neural Network for Interpreting Ultrasonic Readings of Concrete*. in: Proc. 16º World Conference on Nondestructive Testing,. Montreal: (Canada). CD-ROM.

Meneghetti L. C., Padaratz I. J., Steil R. O. (1999), *Use of Ultrasound to Evaluate Concrete Strength in the Early Ages*. in International Symposium on Nondestructive Testing Contribution to the Infrastructure Safety Systems in the 21st Century. Torres: (Brazil).

Naik T. R., Malhotra (1991), V. M., *The ultrasonic pulse velocity method*, in: Malhotra V. M., Carino N. (Editor), *Handbook on Nondestructive Testing of Concrete*, (Boca Raton, Florida, USA): CRC Press, 1991, 343 p.

Nesvijski E. G. (2003), *Dry Point Contact Transducers: Design for New Applications*, The e-Journal of Nondestructive Testing, vol. 9, n. 9,. http://www.ndt.net, Berlin: (Germany).

Nesvijski E. G. (2001), *On Raleigh Equation and Accuracy of its Real Roots Calculations*. Journal of Thermoplastic Composite Materials: vol. 14, n. 5.

Nesvijski E. G., Nesvijski T. C., Lorenzi A. (2000), *Differential Approach to Ultrasonic Testing of Strength and Homogeneity of Concrete.* in International Conference on NDT in Civil Engineering. Tokyo: (Japan).

Nogueira C. L. (2002), *Análise Ultra-Sônica da Distribuição dos Agregados no Concreto através de Wavelets*, in Proc. XXI Congresso Nacional de Ensaios não Destrutivos. Salvador: (Brazil).

Popovics S. (1998), *Strength and Related Properties of Concrete - A Quantitative Approach*, (New York, USA: John Wiley and Sons), 535p.

Popovics S. (1999), *Educational and Research Problems of NDE of Concrete Structures.* in International Symposium on Nondestructive Testing Contribution to the Infrastructure Safety Systems in the 21st Century. Torres: (Brazil).

Qasrawi H. (2002), *Concrete Strength by Combinated Nondestructive Methods – Simple and Reliably Predicted*, Cement and Concrete Research **30**: pp. 739-746.