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RESEARCH ARTICLE

Structural health monitoring: detection of concrete flaws using ultrasonic pulse velocity

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Abstract
Assessment of concrete structures is a mandatory task of engineers to keep the structure safe and well performing. Non-destructive testing methods seem to be more appropriate for this task. They are reliable, quick and does not cause significant damage to the concrete surface. The non-destructive testing application is an interesting strategy to monitor the conditional strategy of the concrete structures, such as homogeneity of material, density, strength evolution, internal defects and flaws in concrete structures. This paper aims to study the homogeneity of the concrete structure using contour mapping technique by interpretation of ultrasonic pulse velocity values. For this study, the authors performed an ultrasonic pulse velocity test on beams and columns of an old car parking shed made of reinforced cement concrete. The contour map generated using velocity values of UPV shows the level of homogeneity. The variations of color in the contour map indicate the presence of defects in the structure. This interpretation strategy will be a suitable tool for assessment of concrete structures.

Keywords Concrete · Ultrasonic pulse velocity · Contour mapping · Homogeneity · Defects · Interpretation

1 Introduction

Reinforced concrete structures play an essential part in the infrastructures in most of the countries. Many of the older structures which were built in the first half of the 20th century are reaching the end of their expected designed life. However, when the concrete structures are not appropriately designed, or production process is inadequately controlled, flaws and defects can be introduced early in the structure. All this defects and flaws can affect the performance and reduce its strength and durability. The worst part is that some of the newer structures were also showing early deterioration and defects. This increasing problem of deterioration gives a strong argument for the validation on new techniques and development of new tools that would allow us to monitor the conditional state of elements and provides the data on their potential service life [1].

In these situations, the application of non-destructive techniques proven to be very suitable for these tasks to check and monitor the conditional state of the constructed facilities, because these are quick, accurate and does not cause any considerable damage to the concrete surface.

The use of these non-destructive technique methods will provide important data to design a preventive maintenance plan. It is known that the early detection of problems for a quick evaluation and intervention.

Over the last few decades, they are several NDT methods came into force from laboratory curiosities to quality control tools in different productive fields. These methods are nowadays commonly using to check the homogeneity in structure, changes in surface, the presence of cracks or other physical characters [2].

Among all NDT techniques available in the market for damage detection and defects detection, Ultrasonic pulse velocity are being used widely in civil engineering applications because of low cost, ease of operation and this test does not cause any considerable damage to the concrete structure surface [3].

2 Non-destructive testing

NDT equipment can be used to assess the condition of existing structures. NDT methods are those that do not cause any damage to the element tested or leave only small lesions that can be rectified easily after the testing is done. In the case of

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newer structures, these tests can be used for monitoring the strength evaluation and to check the quality of the concrete. The properties that can be evaluated with these techniques are density, uniformity, modulus of elasticity and compressive strength, surface hardness, the location of re-bars, gaps and cracks can also be investigated. The main reason for the development of these techniques is the dynamic nature of the concrete quality. The application of these techniques is an interesting tool to check and control these structures. Strength and durability are the most used property to control concrete structures.

Several specific situations in which the use of NDT methods can be considered attractive [4]:

- quality control of construction in situ;
- assessing the potential durability of the concrete;
- determining the position and quantity of reinforcement;
- for the assessment of post-earthquake structural integrity;
- determining the concrete uniformity;
- modification to an existing structure;
- monitoring of structures affected by external works;
- monitoring long-term changes in concrete properties;
- location and determination of the extension of cracks, voids, honey-combing and similar defects within the concrete structure.

One of the objectives of development NDT techniques is a reliable assessment of concrete defects even when there is an accessible only from a single surface. The application of NDT demand will probably increase since aging infrastructure requires regular inspection for early planning of repair and intervention, to ensure structural performance and human safety.

3 Ultrasonic pulse velocity testing

Ultrasonic pulse velocity (UPV) method is useful and flexible which allows in-depth analysis of homogeneity of the material. Using UPV, it is possible to determine concrete homogeneity, quality, deterioration, the presence of internal flaws and voids [5].

Ultrasonic pulse velocity can be used for the detection of cracks and flaws in hardened concrete [6]. In concrete, the standards establish procedures for carrying out the tests, which is performed in order to determine the modulus of elasticity and monitor the variations of concrete characteristics [7]. Using UPV, and to make comparisons with reference specimens, it may estimate potential compressive strength.

For concrete tests, the method is usually based on the use of portable equipment, composed by the source/detector unit and handheld surface transducers, which works in the frequency range of 25–60 kHz [8]. The evaluation of UPV is a complex activity, which requires careful data collection and expert knowledge and sensitivity to obtain a diagnosis. To map the homogeneity of concrete in a structure, it is necessary to interpret and connect a large number of UPV data [5].

3.1 Probing methods of UPV

Three different types of probing methods usually followed to record the experimental values are (Fig. 1):

- *Direct or cross probing:* The receiver and the transmitter are opposite to each other on either side of the cube.
- *Semi direct probing:* The transmitter and the receiver are on any two perpendicular faces of a cube.
- *Indirect or surface probing:* The receiver and transmitter are on the same face of a cube.

3.2 Path length

Theoretically, the path length traveled by the wave and the frequency of the wave (which is the same as the frequency of the transducer) should not affect the propagation time; therefore, they should not affect the pulse velocity. However, in practice, smaller path lengths tend to give more variable and

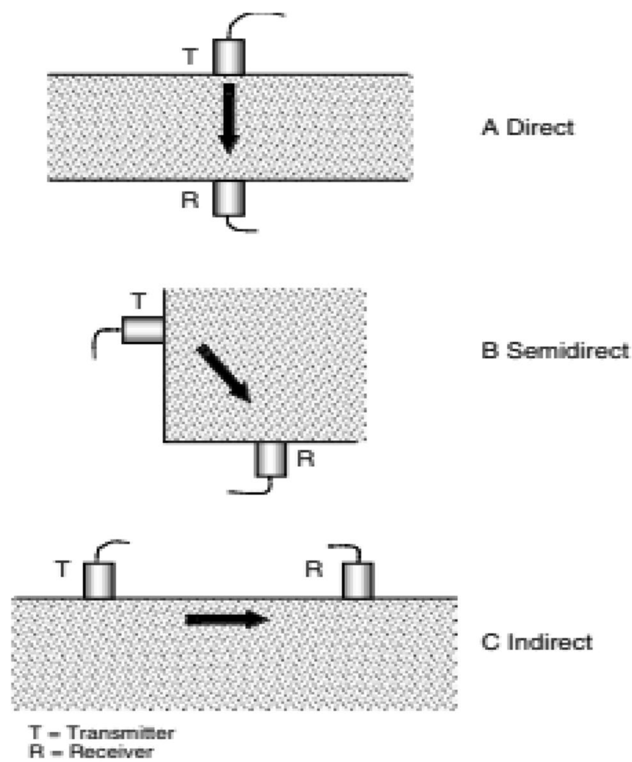


Fig. 1 Pulse velocity measurement configurations. **a** Direct method. **b** Semi-direct method. **c** Indirect surface method. (Courtesy—Naik et al. [9])

slightly higher pulse velocity because of the inhomogeneous nature of concrete [10]. RILEM [11] has recommended the following minimum path lengths:

1. 100 mm for concrete having a maximum aggregate size of 30 mm.
2. 150 mm for concrete having a maximum aggregate size of 45 mm.

3.3 Application of UPV to detect concrete uniformity

Heterogeneities in the concrete within or between members cause variations in pulse velocity which, in turn, are related to variations in quality. Measurements of pulse velocity provide a means of studying the homogeneity and, for this purpose, a system of measuring points which covers uniformly the appropriate volume of concrete in the structure has to be chosen. The number of individual test points depends upon the size of the structure, the accuracy required. In a large unit of reasonably uniform concrete, testing on a 1 m grid is usually adequate but, on small units or variable concrete, a finer grid may be necessary. It should be noted that, in cases where the path length is the same throughout the survey, the measured time may be used to assess the concrete uniformity without the need to convert it to velocity. This technique is particularly suitable for surveys where all the measurements are made by indirect transmission, i.e., surface probing. It is possible to express homogeneity in the form of a statistical parameter such as the standard deviation or coefficient of variation of the pulse velocity measurements made over the grid [12]. The qualitative way of representing the homogeneity of concrete is by contour mapping of the raw UPV data collected by indirect transmission.

3.4 Collection of UPV data

The phase-III of this program was conceived with the idea of detecting the unseen cracks and voids in concrete using ultrasonic pulse velocity testing. For this purpose, the data are to be collected using surface probing methods. The beam was tested using portable PUNDIT equipment, provided with 54 kHz transducers. According to Naik and Malhotra [13], this frequency range was chosen to minimize the influence of concrete strength variations in the measurements. The path length is made fixed as 100 mm for data collection, and a grid of 150 × 150 mm squares is used. 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 contour map of the pulse velocities alongside the beam.

3.5 Contour map

Contour map displays lines/gradients that include points of equal value and separate points of higher value from points of lower value. In this research, a contour map of ultrasonic pulse velocities are generated, which can identify and map voids, honeycomb, cracks, delamination, and other damage in concrete. Imaging is implemented in many fields and has been demonstrated to be a powerful tool for the interpretation of signal data. However, imaging for the evaluation of concrete structures has not been widely used. The generated image shows where the readings are lower or higher. When no variations are shown, concrete is homogenous. Figure 2 represents the contour map generated on a concrete surface.

4 Structure inspection

The car parking shed is an RCC framed structure consisting 2-bays along length and 1-bay in other direction. The apparent height of the column is 180 cm on an average, totally 6 columns. The length of the beam is varying from 290 to 323 cm. This car parking shed was constructed by students itself. The depth of beams 30 cm. The thickness of a brick layer on beam as parapet is around 11 cm. The grade of concrete used for construction is around M20. Figure 3 shows a photograph of a car parking shed. The AutoCAD drawings of car parking shed with measurements and designation to beam and columns are shown in Figs. 4 and 5.

4.1 Visual observation

- Corrosion of rebar.
- Cracks occurred at some places in the beam.
- Spalling of the concrete slab.
- Dampness and fungal growth are observed at some locations.

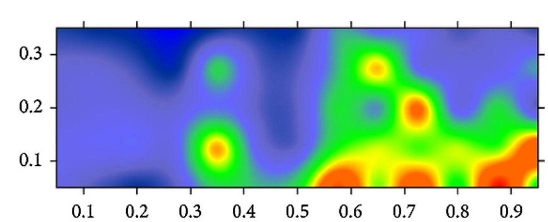


Fig. 2 Contour map generated on a concrete surface (Courtesy—Lorenzi 2014)

Fig. 3 Photograph of car parking shed located at NITT

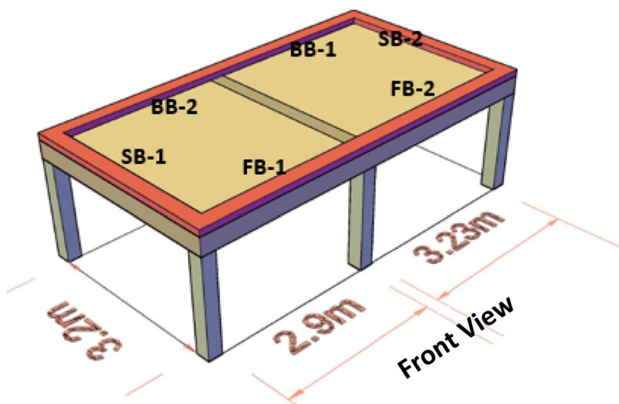


Fig. 4 Auto-CAD sketch of car parking showing the designation to beams

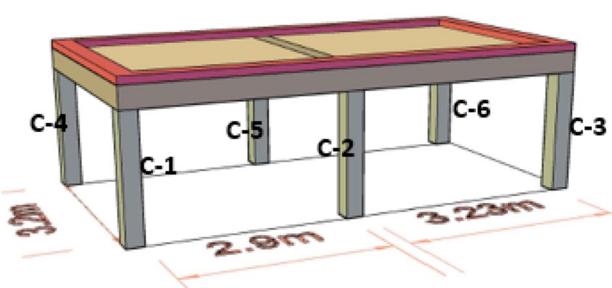


Fig. 5 Auto-CAD sketch of car parking showing the designation to columns

5 Data collection procedure

To ensure the proper positioning of the transducers during the UPV data collection, a grid sheet of 10 × 10 cm

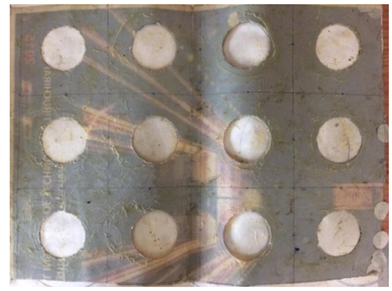


Fig. 6 Grid sheet of 10 × 10 cm size for UPV testing

Fig. 7 Photograph taken while testing of the structure

was prepared which is shown in Fig. 6. During the UPV test, the indirect measurement/surface probing methodology was adopted. The aim of this study is to verify the concrete homogeneity of concrete in the car parking shed using UPV, by mapping the data collected. The photograph taken while testing the structure was shown in Fig. 7.

6 Data mapping

For mapping of the UPV data, the location of the transducer in the grid is expressed as X and Y co-ordinates, and the UPV values are expressed as Z co-ordinate. Each indirect measurement is placed at the midpoint of the line connecting two points of the grid i.e., the indirect UPV measurements are taken at four points that made up a grid cell. The four values corresponding to readings taken between two neighboring horizontal or vertical grid points were positioned at the midpoint between these points. The map generated by plotting these values will show the variations in concrete homogeneity, determining region inside the concrete presenting differences in homogeneity. The pattern of data collection is represented in Fig. 8.

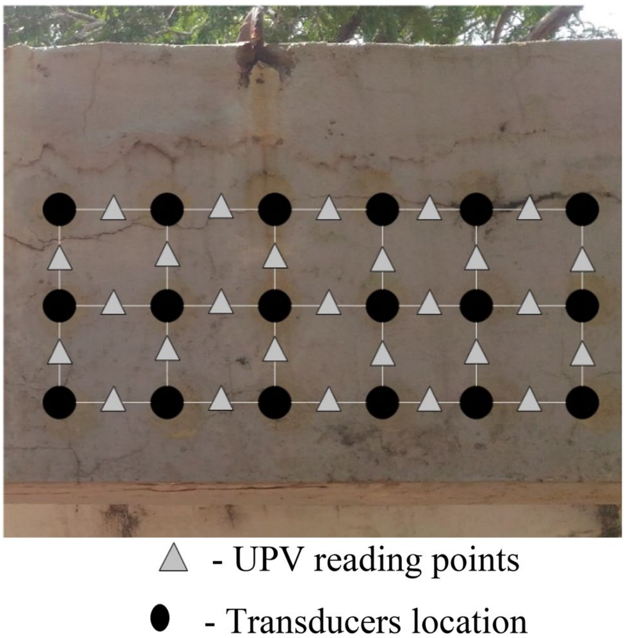


Fig. 8 Illustration showing the position of transducers and data collection points of UPV testing

6.1 Fixing gradient for contour map

The contour gradient for the contour map is fixed based on the ultrasonic pulse velocity criterion given in Table 3 of Condition Assessment of Buildings for Repair and Upgrading, Prepared under-GoI-UNDP Disaster, Risk Management Programme National Disaster Management Division Ministry of Home Affairs, Government of India New Delhi June 2007. Table 1 gives the velocity criteria and the corresponding concrete quality and contour gradient.

7 Results

As a prior test to prove the capacity of UPV to detect the homogeneity of the concrete surface, three concrete specimens, i.e., one cube of 10 × 10 × 10 cm, one cube of 15 × 15 × 15 cm and one beam of 10 × 10 × 50 cm were built with objects inside to simulate the imperfections or defects that could exist in the real structural elements.

Figure 9 shows the casted specimens. The mix proportion used to prepare the concrete specimens were 1:1.41:2.69 (cement:natural river sand:coarse aggregate), with a w/c ratio of 0.37, this resulted in a slump of 20 mm and a 28th-day compressive strength of 48.25 Mpa, i.e., M40 grade of concrete.

After the curing period, a mesh of 5 × 5 cm has drawn on all the specimens to proceed the UPV reading of the concrete specimens. UPV tests were performed with a portable device, equipped with low frequency (54 kHz) transducers.

To ensure proper positioning of the transducers during the UPV readings, a grid of 5 × 5 cm lines were drawn (i.e., a measurement sheet was used to ensure the perfect positioning of the transducers during the tests) on all sides of all specimens. Figure 10 shows the grids that are drawn for proper positioning.

The main objective of the test was to collect UPV data and verify if the analysis of the results could allow the

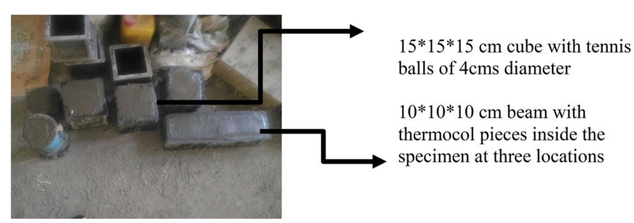


Fig. 9 Casted specimens

Table 1 Velocity criteria and the corresponding concrete quality and color gradient

S. no.	UPV value in km/s (V)	Concrete quality	Color gradient (chosen by author)
1	V greater than 4.0	Very good	White
2	V between 3.5 and 4.0	Good, but may be porous	Green
3	V between 3.0 and 3.5	Poor	Red
4	V between 2.5 and 3.0	Very poor	Yellow
5	V between 2.0 and 2.5	Very poor and low integrity	Orange
6	V less than 2.0 and reading fluctuating	No integrity, large voids suspected	Blue

Fig. 10 **a**, **b** Grids are drawn on specimens

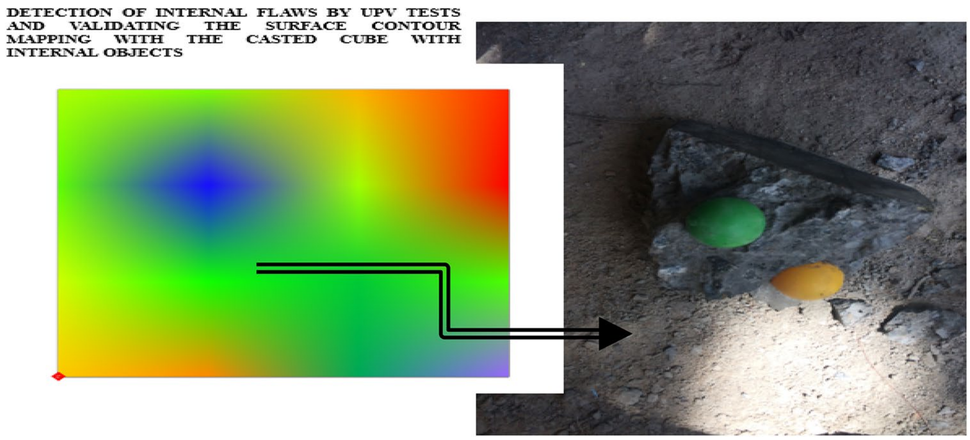


Fig. 11 Core samples of a concrete cube of the 15 × 15 cm showing the presence of tennis ball inside concrete

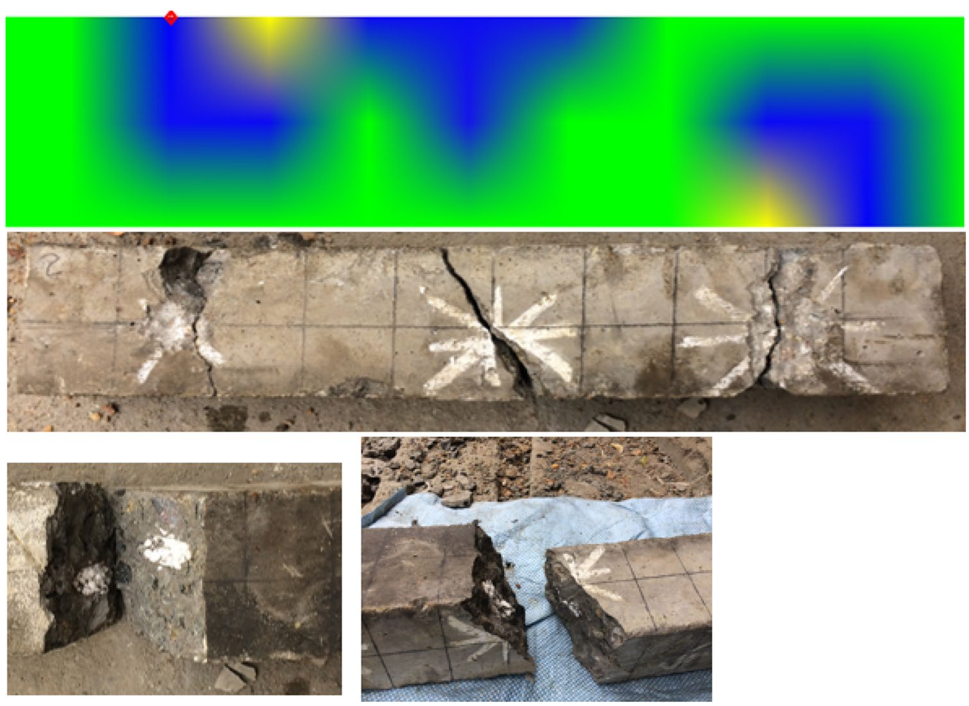
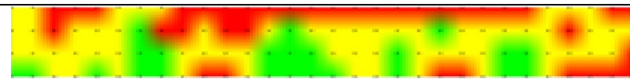
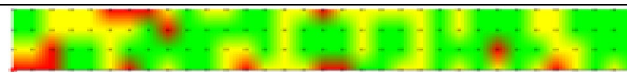
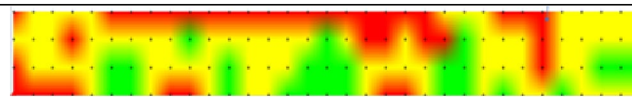
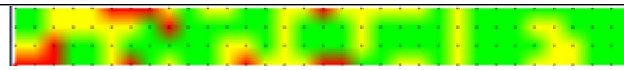
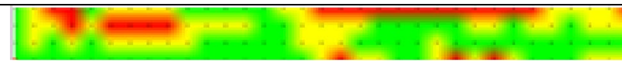
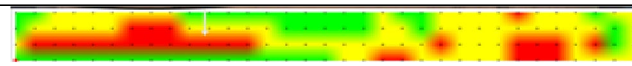
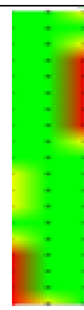
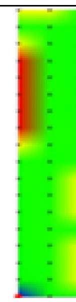
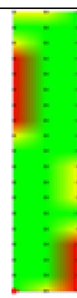
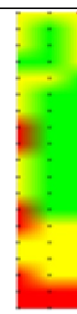
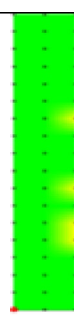
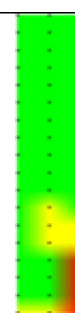


Fig. 12 A core sample of beam showing the presence of thermocol

Table 2 Description of specimens and objects used to induce defects in specimens

Type of specimen	Type of object used	Object size	Type of defect simulated
10 × 10 × 10 cm cube	–	–	–
15 × 15 × 15 cm cube	Tennis ball	4 cm diameter	Very large void or honeycomb
10 × 10 × 50 cm beam	Thermocol	5 × 5 × 1.5 cm	Honeycomb or crack

Table 3 Contour map of UPV results for beams and columns of car shed

S.No	Designation	Contour Map		
Beams				
1	FB-1			
2	FB-2			
3	BB-1			
4	BB-2			
5	SB-1			
6	SB-2			
Columns				
7, 8	C-1		C-2	
9,10	C-3		C-4	
11,12	C-5		C-6	

detection of the objects inside the specimens. Surface mapping technique was used to interpret of results, as reported by Lorenzi et al. [14].

In order to check if the diagnosis made using the contour map images was reliable or not, the samples were broken at the points chosen based solely on the contour images. Figures 11 and 12 show the suspicious zones which are coinciding with the concrete specimen defects, providing clear evidence that the defects were accurately located using only NDT data, with no prior knowledge of their position.

Since the results got with known deformities are pleasing the car shed was tested for its concrete homogeneity. The contour map obtained for every element of the car shed is tabulated below in Table 3. Refer Figs. 4 and 5 for beam and column designations.

On referring Table 2 for the concrete quality, the cube of 15 × 15 cm is showing the contour map pointedly with blue color which depicts the exact location of the tennis ball knowingly kept inside the concrete cube. The beam contour map has three points of blue color on the beam showing the position of thermocol placed in the concrete beam.

From Table 3, it is understood that beams are having more internal voids and cracks widespread. Among them FB-1, BB-1 and SB-2 are having more damages than other beams. Among the columns, C-4 has more damages whereas, other columns are in good condition.

The beams and columns are having more amount of green color where the concrete is said to be good. The red colour in the beam and column indicate that the concrete is poor the yellow color in the beam and column indicate that the concrete is very poor.

8 Conclusions

This study shows that the interpretation strategy of UPV data by contour mapping is adequate to organize and analyze the results. The use of grids to collect data works well and ensures that no region was overlooked. And from the contour map, the presence of non-homogeneous spots inside the structure is well identified. This study demonstrates that the UPV test can be used to locate the pattern of cracks in the concrete structure. In the car parking shed, the contour map of the beam shows significant variations in color which shows heterogeneity in the concrete. Whereas in columns, the contour map has a widespread green color which means the velocity variation between 1500 and 3500 m/s which indicates moderate strength. Hence the column is in good condition, but beam needs immediate repair. The results of this study indicate that UPV, combined with the generation of surface contour maps may detect heterogeneity in concrete structures if any and these techniques contribute to a quick condition assessment of concrete structures. This study indicates that UPV tests are sensitive to variations in density and homogeneity and therefore may supply essential data for decision-making on the conditions of concrete structures, i.e., UPV tests can contribute for the quality control of concrete structures. The generated maps for the columns by UPV data indicates the level of homogeneity is more, whereas the contour map of beam shows significant variations in color which shows heterogeneity in the concrete surface as well as internally. Visualization tools may indicate the condition of the concrete structure, suggesting that this may be the best strategy to perform accurate analyses. The 10 × 10 cm grid seemed to be useful in the case of columns, and 15 × 15 cm showed effective in the case of beams. Hence, grid size depends upon the accuracy we want and also sometimes depends upon the size of the element under consideration.

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