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Detection of Concrete Damage Using Ultrasonic Pulse Velocity Method

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Abstract

This paper investigates the efficiency of Ultrasonic Pulse Velocity (UPV) method in detecting cracks and flaws inside the concrete. A series of concrete beams and slab specimens were cast and damaged to simulate the different mechanisms possible in a reinforced concrete deck due to mechanical loading. Two types of simulated cracks, namely, cracks perpendicular and cracks parallel to axis of beam were induced without actually breaking the beam. An ideal vertical crack was simulated by introducing a cut perpendicular to the axis of the beam using a diamond tipped concrete cutter and a real crack was simulated by inserting a thin sheet of plastic while casting the beam. Horizontal cracks were simulated using lower acoustic impedance materials like thermocole and polyvinyl chloride inserted at a known distance while casting the specimen. Materials with less acoustic impedance as compared to that of concrete have good reflectivity and hence would simulate the damage accurately. The results indicate that the pulse velocity method can be used effectively to measure the crack depth of vertical cracks. The depths can be measured with high degree of accuracy, if the distance between the transducers is maintained between 100 - 200 mm. However, for horizontal cracks, this method does not prove to be accurate and effective in measuring the location of cracks. But within a distance of 100-200 mm between the transducers, the depth of the horizontal cracks can be estimated to a reasonable degree of accuracy. Hence, the distance between the transducers plays a vital role in the accuracy of depth measurement. This is because, if the distance between the transducers is less than 100 mm, then the surface wave reaches the receiver before the reflected compression waves and leads to lower values of depth. Also, if the depth is more than 200 mm, there are possibilities of multiple reflections and hence there is an error in measurement.

Keywords: *Pulse velocity, Non-destructive test, Crack depth, Concrete damage*

1. Introduction

One of the principal objectives of the development of NDT techniques is a reliable assessment of defects of concrete members even when they are accessible only from a single surface. Especially on reinforced concrete structures such inspections could in the past only be solved by means of radiography (for concrete thickness less than 0.6 m) or by using more or less destructive methods. When some of the established methods used in other areas of materials testing are applied to concrete testing, certain difficulties are encountered as concrete is an inhomogeneous, porous building material. There are mainly three ways of non destructive testing using ultrasonic techniques viz. Impact echo method, Pulse echo method and Pulse velocity method [1].

In this experimental work, ultrasonic pulse velocity is used to determine the crack depths in concrete. The test instrument consists of a means of producing and introducing a pulse into the concrete (pulse generator and transmitter), a means of accurately measuring the time taken by the pulse to travel through the concrete.

A pair of piezoelectric sensors is placed at opposite ends of the test member. In one of the sensors, electronic pulses are generated and the time it takes for the pulse to propagate through the concrete is measured by the other sensor. Knowing the distance traveled, propagation velocity is calculated and based on the velocity, condition of the concrete is determined. Depending on the locations of the sensors, the procedure is divided in to three categories: direct (sensors at opposite ends), indirect (sensors on the same sides), and semi-direct (sensors at right angles) transmission. Indirect measurement is used in this study to assess the crack location in concrete.

2. Materials and Experimental Methods

2.1 Mixture Proportions

Grade 43 Portland cement was used for the study. 25 mm and 12.5 mm maximum sized coarse aggregates were used for Normal concrete (NC) and self compacting concrete (SCC) respectively. SCC mixes were used in order to simulate horizontal cracks with ease. River sand with a fineness modulus of 2.10 were used. Fly ash and a carboxylic ether polymer with long side chains based super plasticizer was used in the SCC mixture. Viscosity modifying agents were also used to avoid segregation in SCC mixes. The mixture proportions for the above said mixtures are given in Table 1.

Three different types of concrete specimens were cast using the below mixtures. Cracks were simulated and studied on all the types.

Table 1: Mixture Proportions (Note: the weights shown are in kg per 100kg of concrete)

Mixture designation /Ingredients	**Normal Concrete**	**Self Compacting Concrete**
Cement	13.33	16.3
River sand	26.67	35.5
25 mm Aggregate	53.33	0
12.5 mm aggregate	0	28.7
Water	6.67	8.7
Fly ash	0	10.3
Glenium 51	0	0.20
VMA	0	8×10^{-4}

- Beam (type 1) dimensions – 100mm x 100mm x 500mm
- Beam (type 2) dimensions – 150mm x 150mm x 750mm
- Cube dimensions – 150mm x 150mm x 150mm

The specimens were kept in curing tank for a period of 7 days.

2.2 Crack / Fault Simulation in Concrete

2.2.1 Simulation of Vertical Crack

An ideal vertical crack was simulated in a beam by a diamond tipped concrete cutter perpendicular to the axis of the beam to different depths. A real crack was simulated in the beam by using a thin sheet of plastic (1 mm thick) while casting the beam.

2.2.2 Simulation of Horizontal Crack

Materials with acoustic impedance (table 2) much lesser than that of concrete were used to simulate the horizontal cracks. Materials used in this experiment are:

i) Thermocole

ii) PVC (Poly Vinyl Chloride)

The above materials were inserted in the concrete at the time of casting.

Table 2: Acoustic impedance values

S. No	Material	Velocity of sound	Density	Acoustic Impedance
		(m/sec)	(Kg/m^3)	(g/m²sec)
1	Concrete	4400	2400	10.56×10^6
2	Thermocole	133.33	8.5	1133.3
3	PVC	2000	1427	2.854×10^6
4	Recycled Plastic	857	940	8.06 x 105

2.3 Principle and Crack Depth Estimation

The ultrasonic pulse transmits a very small amount of energy through air. Therefore, if a pulse traveling through the concrete comes upon an air filled crack or a void whose projected are perpendicular to the path length is larger than the area of the transmitting transducer; the pulse will get diffracted around the defect. Thus, the pulse travel time will be greater than that through a similar concrete without any defect. The pulse velocity method, therefore, is effective in locating cracks, cavities, and other such defects. It should be pointed out that the application of this technique in locating flaws has serious limitations. For example, if the cracks and flaws are small or if they are filled with water or other debris, thus allowing the wave to propagate through the flaw, the pulse velocity will not significantly decrease, implying that no flaws exist.

2.3.1 Vertical crack

The experimental set up for estimating the vertical crack is as shown in the Fig. 1. The depth of an air filled crack can be estimated by the pulse velocity method [2]. The depth, h, is given by equation (1),

$$h = \left(x / T_2\right)\left(T_1^2 - T_2^2\right)^2 \qquad (1)$$

Where

x = distance of transducer from the crack (note that both transducers must be placed equidistant from the crack);

T_1 = transmit time around the crack;

T_2 = transmit time along the surface of the same type of concrete without any crack (note that surface path length for T_1 and T_2 must be equal).

It should be pointed out that for the above equation to be valid; the crack must be perpendicular to the concrete surface. A check should be made to determine if the crack is perpendicular to the surface or not. This can be done as follows.

Place both the transducers equidistant from the crack and obtain the transit time. Move each transducer, in turn, away from the crack. If the transmit time decreases, then the crack slopes towards the direction in which transducer was moved.

2.3.2 Horizontal Crack

The experimental set up for estimating the horizontal crack depth is as shown in the Fig. 2.

The transmitter is fixed at a point and the position of the receiver is changed every time.

The travel time of the pulse wave is recorded. Knowing the velocity of the pulse wave (compression wave) through the concrete the depth of the horizontal crack can be estimated from the equation (2),

$$y = 0.5\sqrt{\left(V^2T^2 - x^2\right)} \qquad (2)$$

Where

y = depth of the horizontal crack;

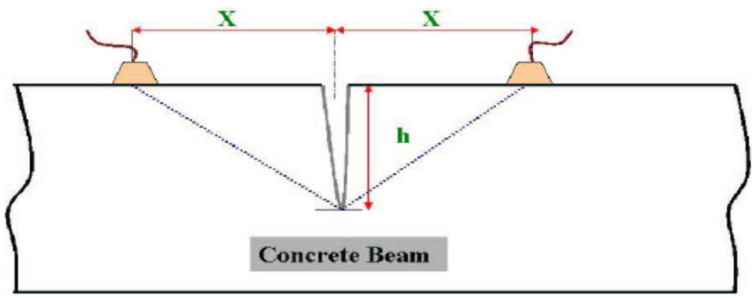

Fig.1: Experimental set-up for vertical crack depth estimation

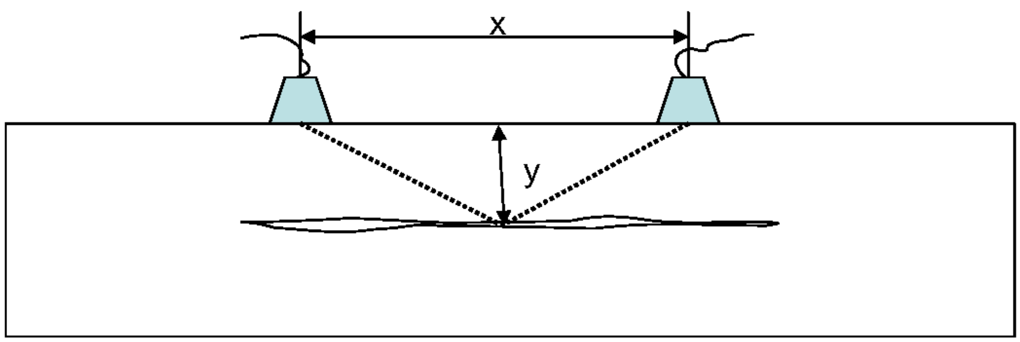

Fig.2: Experimental set-up for horizontal crack depth estimation

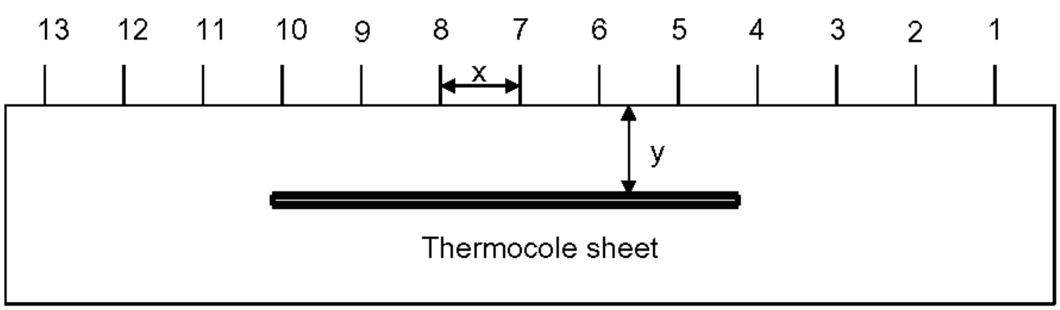

Fig.3: Setup for beam 1

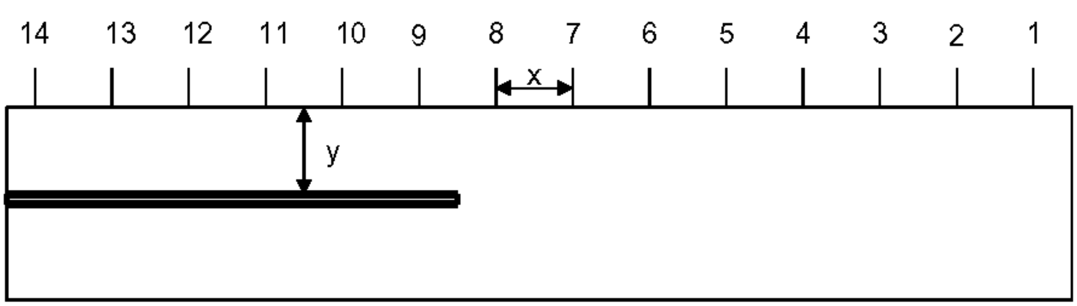

Fig.4: Setup for Beam 2

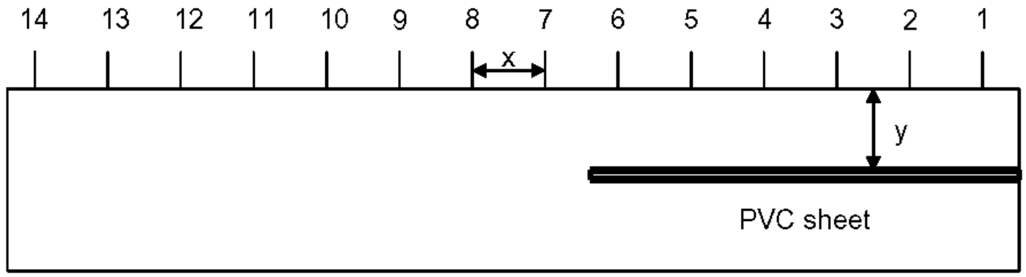

Fig.5: Setup for Beam 3

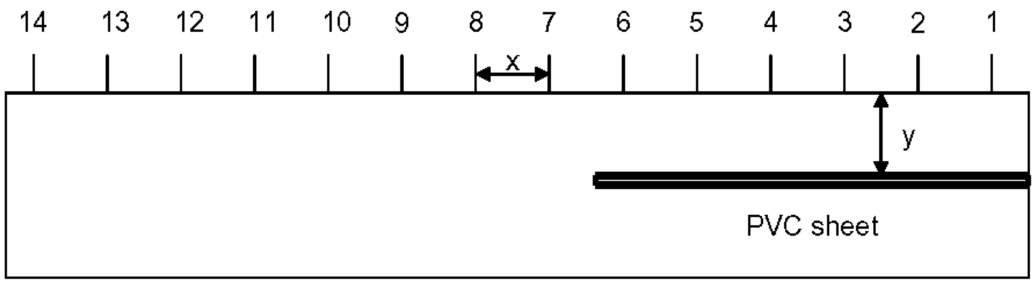

Fig.6: Setup for Beam 4

V = velocity of the compression wave through the concrete; x = distance between the two transducers; T = transit time.

It should be noted that if the distance etween the two transducers is small, the surface wave will reach the receiver before the compression wave. Therefore, a minimum distance (150mm – 200mm) should be maintained between the transmitter and the receiver to ensure that the wave reaching the receiver is a compression wave.

3. Results and discussion

3.1 Measurement of vertical crack depth

The values of the crack depths measured on beam of dimensions 100mm x 100mm x 500mm are shown in the table 3.

The values of the crack depth measured were inaccurate because the dimensions of the beam were approximately equal to the wave length of the ultrasonic wave through the concrete.

Table 3: Measurement of Crack depths on beam of type 1

S. No.	Depth of actual crack	x	T1	T2	Crack depth measured
	(cm)	(cm)	(μs)	(μs)	(cm)
1	4.1	10	95.6	75.8	7.68
2	4.1	20	189.5	152.9	14.64

The values of the crack depths measured on beam of dimensions 150mm x 150mm x 750mm are shown in the table 4. In this test the beam was tested for different depths namely 7.1 cm, 10.35 and 11.55 at the same location. After completing the test with a depth of 7.1 cm, the beam was again cut at the same location using the concrete cutter to reach the depth of 10.35 cm and so on.

The crack depths can be measured accurately if the transducers are kept closer to the crack. If the distance between the transducer and the crack is more then we don’t get accurate results. When the transducers are kept closely to the crack the ultrasonic wave gets diffracted about the crack. But when the distance is large the wave travels through the concrete and does not diffract around the crack. Hence for larger values of x we don't get accurate results.

Table 4: Measurement of Crack depths on beam of type 2

S. No.	Depth of actual crack	x	T1	T2	Crack depth measured
	(cm)	(cm)	(μs)	(μs)	(cm)
1	7.1	5	60	35	6.96
2	7.1	10	80	58.4	9.36
3	7.1	20	141.5	103.7	18.56
4	7.1	30	196.7	153.5	24.03
5	10.35	5	79.0	34.5	10.29
6	11.55	5	91.3	36.5	11.46

3.2 Measurement of Horizontal Crack Depth

Four beams were tested for the estimation of horizontal crack depths. The cracks were simulated in the beams at different locations with different materials. SCC was used in this test so that to position the materials at desired location. There were some slight changes in the position of the simulated cracks due to the weight of the concrete flowing over the materials. After demoulding the accurate depth of the actual crack was measured using a ruler from the sides of the concrete.

3.2.1 Beam 1

The set up of the experiment is shown in the Fig. 3. The distance between two points is kept constant (x = 5cm). The values of transit time are shown in table 5. The depth of thermocouple sheet, y = 50cm from top. Velocity of the compression wave through concrete = 3431m/s.

Table 5: Measurements of depth of horizontal crack in beam 1

S.No.	Pts	x(cm)	t(μs)	y(cm)
1	1-2	5	16.2	-
2	1-3	10	36.6	-
3	1-4	15	56.5	-
4	1-5	20	70.3	-
5	1-6	25	98.7	-
6	1-7	30	112.3	-
7	1-8	35	128.9	-
8	1-9	40	144.3	-
9	1-10	45	195.5	-
10	4-5	5	16.7	14
11	4-6	10	41.9	51.6
12	4-7	15	54.9	56.96
13	4-8	20	83.2	101.84
14	4-9	25	98.4	113.44
15	4-10	30	112.8	122.25

This technique does not give very accurate results for horizontal crack depths. However we can get reasonably accurate results when the distance between the transducers is around 100-200 mm. If the distance between the transducers is less than this the surface wave reaches the receiver before the reflected compression waves and hence we get lower values of depth. When the distance is more than this, there are possibilities of multiple reflections, hence we get incorrect values of depth.

3.2.2 Beam 2

The set up of the experiment is shown in the Fig. 4. The distance between two points is kept constant (x = 5cm). The vales of transit time are shown in table 6. The depth of thermocouple sheet, y = 50cm from top. Velocity of the compression wave through concrete = 3627m/s.

In this case the thermocoule sheet was bent during the time of casting, and hence we have got reasonably accurate results only at some points.

Table 6: Measurements of depth of horizontal crack in beam 2

S.No.	Pts	x(cm)	t(μs)	y(cm)
1	14-13	5	35.7	59.72
2	14-12	10	63.5	103.76
3	14-11	15	57.4	72.18
4	14-10	20	75.2	92.72
5	14-9	25	91.4	108.85
6	14-8	30	105.8	119.6
7	14-7	35	136.5	175.07
8	14-6	40	196	-
9	14-5	45	213.2	-
10	14-4	50	226.8	-
11	9-8	5	13	-
12	9-7	10	27.1	-
13	9-6	15	43.0	-
14	9-5	20	73.2	-
15	9-4	25	89	-
16	9-3	30	103.5	-
17	9-2	35	119.5	-
18	9-1	40	135.2	-

Table 7: Measurements of depth of horizontal crack in beam 3

S.No.	Pts	x(cm)	t(μs)	y(cm)
1	1-2	5	30.7	59.79
2	1-3	10	38.9	65.14
3	1-4	15	53.1	83.31
4	1-5	20	66.1	97.31
5	1-6	25	80.5	115.12
6	1-7	30	93.0	126.65
7	1-8	35	128.7	-
8	1-9	40	140.3	-
9	6-7	5	17.4	-
10	6-8	10	36.7	-
11	6-9	15	53.7	-
12	6-10	20	67.0	-
13	6-11	25	79.0	-
14	6-12	30	92.8	-
15	6-13	35	104.2	-

3.2.3 Beam 3

The set up of the experiment is shown in the Fig. 5. The distance between two points is kept constant (x = 5cm). The values of transit time are shown in table 7. The depth of PVC sheet, y = 100 cm from top. Velocity of the compression wave through concrete = 4222m/s.

In this case also we were able to measure the depths with reasonable accuracy when the distance between the transducers was 150-200 mm.

3.2.4 Beam 4

The set up of the experiment is shown in Fig. 6. The distance between two points is kept constant (x = 5cm). The vales of transit time are shown in table 8. The depth of PVC sheet, y = 75 cm from top. Velocity of the compression wave through concrete = 3877m/s.

Table 8: Measurements of depth of horizontal crack in beam 4

S.No.	Pts	x(cm)	t(μs)	y(cm)
1	1-2	5	15.1	15.22
2	1-3	10	41	61.78
3	1-4	15	56.6	80.08
4	1-5	20	67.9	85.58
5	1-6	25	80.3	92.77
6	1-7	30	95.6	108.82
7	1-8	35	109.5	120.13
8	1-9	40	123.3	130.87
9	6-7	5	14.5	-
10	6-8	10	40.5	-
11	6-9	15	56.7	-
12	6-10	20	70.9	-
13	6-11	25	83.1	-
14	6-12	30	99.6	-

In this case also we were able to measure the depths with reasonable accuracy when the distance between the transducers was 150-200 mm.

4. Summary

The experimental results proved that Ultrasonic pulse velocity method can be used effectively for detection of cracks and flaws in hardened concrete. However, the results will be inaccurate if the distance between the transducers is more than 100 mm. The reason could be the wave does not diffract about the crack. This method does not prove to be accurate and effective in case of horizontal crack depth measurement.

But the horizontal depth can be measured to a reasonable degree of accuracy if the distance between the transducers is maintained between 100 – 200 mm. This is because the surface wave reaches the receiver before the compression wave if the distance between the transducers is less than 100 mm and there are possibilities of multiple reflections if the distance between the transducers is more than 200 mm. Hence, there is an error in measurement. Thus the distance between the transducers plays a vital role in crack depth measurement for both vertical and horizontal crack depths.

5. Acknowledgement

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6. References

1. Malhotra V. M. and Carino N. J., “Handbook on nondestructive testing of concrete”, second edition, ASTM International, CRC press, Chapter 8, 2004.
2. Malhotra V. M., “Testing hardened concrete: Nondestructive methods”, ACI/IOWA state university press, USA, Chapter 5, 74-102, 2004