Experimental study of crack depth measurement of concrete with ultrasonic pulse velocity (UPV)

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Abstract. This research was conducted to know the effect of reinforcement and distance transducer effective in detecting the depth of concrete cracks. The test specimen used is a 15x15x60 cm$^3$ concrete beam with a concrete quality of 19 MPa. The test material is made of artificial cracks as depth as ±2cm, ±4cm, ±6cm, and any fractured variation made 3 pieces of specimen, in addition to the test object was given a reinforcement of Ø8 mm which is placed horizontally in the center of the beam at a depth of 4 cm from the concrete surface. This testing using indirect method with variations of transducer distance of 3cm, 6cm, 9cm, and 12cm. The study concluded that the accuracy of UPV testing results was influenced by reinforcement and distance transducer. Test specimen with an artificial crack depth of ±2cm and ±4cm have a greater reading result with a relative error of 36.8% and 16.5%, while the test object with an artificial crack depth of ±6cm has a smaller reading result with a relative error ±3.4%. In addition, it obtained an effective transducer distance of 12cm with an accuracy of 85.4%.

1. Introduction
Cracks in concrete are important information in identifying the strength of reinforced concrete structures. The existence of concrete cracks, before steel reinforcement become yield is the best structural failure mechanism in a reinforced concrete design because the failure is ductile (under reinforcement). Cracks are an early warning of the structure, so the structure strength can be immediately evaluated to determine the repair or reinforcement of the structure.

The measurement of crack depth can be conducted by Ultrasonic Pulse Velocity Test (UPVT). The principle of this UPV testing work is to transmit the ultrasonic waves from the transmitter to the receiver through concrete material so that the wave is measured by the Read-Out PUNDIT unit (Portable Unit Non Destructive Indicator Tester). Transmitter distance to the receiver is determined before measurement, the ultrasonic wave velocity in concrete material can be calculated and can be used to determine the depth of the crack.

The results of several crack depth measurements with UPVT give different results in the testing of reinforced concrete of the same quality. This raises doubts about the results of measurements with UPV. Therefore, this research needs to be done to determine the influence of steel reinforcement of reinforced concrete and the effective distance of the transducer in the measurement of concrete crack depth.
2. Literature Review

Roberto C A Pinto et al. [4] observed about use of ultrasound to estimate the depth of surface opening cracks in concrete structures with the purpose of knowing and estimating the UPV method is the most effective in estimating crack depth in concrete. The measurement in this study uses indirect methods with 4 different data collection methods, namely the Bungey method, BS 1881 method, and 2 methods made by the author (method A and Method B).

![Figure 1. The measurement method used](image)

The results of this study shows that the BS 1881 method has a correction value of less than 10%, smaller than the 3 other methods used so this method is the most effective method.

This research to know the influence of the reinforcement of the crack depth is also conducted by Herlambang [3] observed effect of distance of transducer and reinforcement on measurement crack depth of concrete using Ultrasonic Pulse Velocity (UPV). The purpose of this research is to know the difference in the results of cracking depth in concrete with deform and plain reinforcement with concrete without reinforcement. The research uses a variation in the crack depth of 10 mm, 20 mm, and 30 mm with testing using 3 variations of transducer distance of 10 cm, 14 cm and 18 cm. Testing using 3 beam samples measuring 15 x 15 x 60 cm for each variation in depth cracks. The test object uses a basic reinforcement of Ø 10 mm and a dash Ø 6 mm. The results gained from the study showed that the reading of crack depth in reinforced concrete and unreinforcement concrete had differences in reading results.

Wibowo et al. [6] observed accuracy of crack depth measurements on reinforced concrete beams using UPV with variations in the thickness of concrete covers with the aim to measure the accuracy of the crack depth measurement Using Ultraviolet Pulse Velocity method on reinforced concrete with the influence of thick difference of concrete cover. The study uses 15 reinforced concrete beams with 4 thick variations of concrete cover and 1 beam variation without reinforcement. Thickness variations of blankets used are 2 cm, 3cm, 4cm, and 5 cm with 1 variation using 3 test specimen with dimensions 15 x 20 x 50 cm. test objects using longitudinal reinforcement (elongated) Ø 8mm and transversal reinforcement (transverse) Ø 6 mm with crack depth Made of 8cm. The results of this study indicate that there is a relative error in artificial crack depth measurements with UPV tests. The relative average error on concrete with thicker concrete cover 2 cm, 3 cm, 4 cm, and 5 cm in a row – also 6.80%; 6.63%; 5.48%; and 4.91%. In concrete without reinforcement has a relatively average error – an average of 4.59%. The results of the analysis obtained that the larger the thickness value of the concrete cover owned, the smaller the value of error relative to the reading of the crack depth.
3. **Summary of Design Equations from Standards**

PUNDIT (*Portable Non-destructive Digital Indicated Tester Unit*) or UPV (*Ultrasonic Pulse Velocity*) is a device that uses ultrasonic waves to determine uniformity, concrete quality, concrete density and crack depth. Factors that influence wave propagation include the maximum diameter of the aggregate, compressive strength, age of the specimen, humidity of the test specimen, temperature of the specimen, steel reinforcement, and uniformity. Some of the rules are reference: ASTM C597-02, EN 12504-04. In general, the UPV testing equation is based on ASTM C597 [1]:

\[ V = \frac{L}{T} \]  

Where;
- \( V \) = Pulse velocity (m/s)
- \( L \) = Distance between Transducer with receiver (m)
- \( T \) = Travel time (s)

The concrete crack depth estimation uses the Indirect Method method which is used to measure the wave propagation time from the transmitter to the receiver on a surface area where time passes the crack line. To determine the crack depth of the concrete, 2 (two) wave propagation measurements were carried out. The first is the transmitter and receiver placed across one surface with the same distance from the surface crack line, that is distance \( X_1 \), and then at distance \( X_2 \). Illustration of measurements as shown below:

The crack depth (c) can be calculated by the following equation:

\[ c = \frac{1}{2} \sqrt{\frac{x_2^2 t_2^2 - x_1^2 t_1^2}{t_2 - t_1}} \]  

Where:
- \( X_1 \) : distance between transducer at first measurement
- \( X_2 \) : distance between transducer at second measurement
- \( t_1 \) : wave propagation time at first observation
- \( t_2 \) : wave propagation time at second observation

![Figure 2. illustration of concrete crack measurement](image)

If at the first measurement the distance between the crack position and the transmitter is \( b \), and the distance between the receiver and the crack position is also \( b \) in the opposite direction, then \( X_1 = 2b \). Next, if the measurement of the distance between the crack position and the transmitter is \( 2b \), and the distance between the receiver and the crack position is also \( 2b \) in the opposite direction, then \( X_2 = 4b \). Then the measurement illustration can be described as:
Equation (2) above becomes:

$$c = b \sqrt{\frac{4t_1^2 - t_2^2}{t_2^2 - t_1^2}}$$

(3)

4. Experimental Program

4.1 Test specimens

The specimens used in this study were beam-shaped specimens with dimensional of 15x15x60 cm and concrete quality of 19 MPa. The specimens were given artificial cracks with variations in crack depth of ±2 cm, ±4 cm, ±6 cm, and each variation of cracks was made 3 pieces of specimens, in addition to the specimens were given Ø8 mm reinforcement placed transversely in the middle of the beam at depth 4 cm from the concrete surface. For more details, the concrete specimens to be made are shows in Figure 3 and Table 1.

| No | Specimen | Size (cm x cm x cm) | Crack depth (cm) | Transducer Distance (b) (cm) | Quantity |
|----|----------|---------------------|------------------|-------------------------------|----------|
| 1  | B 19.2   | 15 x 15 x 60        | ±2               | ±2, ±4, ±6                   | 3        |
| 2  | B 19.4   | 15 x 15 x 60        | ±4               | 3, 6, 9 & 12                 | 3        |
| 3  | B 19.6   | 15 x 15 x 60        | ±6               | 3                            | 3        |

4.2. Test setup

This test set up is adapted to the standard UPV testing standards, using the PUNDIT tool. Estimation of concrete crack depth measurement measured by Indirect method. The method used to measure the time of wave propagation from the transmitter to the receiver is on one surface area where time passes through the crack line. To find out the depth of the crack, 2 (two) wave propagation measurements were carried out. The first, the transmitter and receiver are placed across one surface with the same distance from the surface crack line, that is at distance b. Second, the transmitter and receiver are removed as 2b. Illustration of measurements as in the following image.

![Figure 3. Concrete Crack Depth Testing scheme](image)

Note:
1. Read out PUNDIT
2. Connector
T. Transmitter
R. Receiver
h. Crack Depth
h. Transducer Distance
5. Test Results
The test results for all specimens are shown in Table 2 and Table 3, these results shows differences in the depth reading of the measurement results (H measure) against artificial cracks (H artificial) for each of the specimen. These results are stated in error relative to the artificial crack's depth value.

Table 2. Summary of test result for the crack depth 2 cm

| Specimens | Transducer distance b (cm) | T1 (µs) | T2 (µs) | H Measurement (cm) | H Artificial (cm) | Error relative (%) |
|-----------|---------------------------|---------|---------|--------------------|-------------------|--------------------|
| B 19.2.01 | 3                         | 22.77   | 36.63   | 2.50               | 2.00              | 25.00              |
|           | 6                         | 36.00   | 66.40   | 2.95               |                   | 47.50              |
|           | 9                         | 53.20   | 102.00  | 3.03               | 2.00              | 51.67              |
|           | 12                        | 81.07   | 158.10  | 3.13               |                   | 56.67              |
Table 3. Summary of test result for the crack depth 4 cm

| Specimens | Tranducer distance b (cm) | T1 (µs)  | T2 (µs)  | H Measurement (cm) | H Artificial (cm) | Error relative (%) |
|-----------|---------------------------|----------|----------|--------------------|-------------------|--------------------|
| B 19.2.02 | 3 | 34.67 | 53.60 | 3.20 | 2.00 | 60.00 |
|           | 6 | 45.90 | 84.05 | 3.22 | 2.00 | 61.06 |
|           | 9 | 57.70 | 111.50 | 2.77 | 2.00 | 38.33 |
|           | 12 | 85.30 | 166.60 | 2.83 | 2.00 | 41.67 |
| B 19.2.03 | 3 | 28.17 | 45.73 | 2.67 | 2.00 | 33.33 |
|           | 6 | 40.60 | 76.30 | 2.67 | 2.00 | 33.65 |
|           | 9 | 56.20 | 109.83 | 2.10 | 2.00 | 5.00 |
|           | 12 | 68.43 | 135.60 | 1.78 | 2.00 | 11.21 |

6. Discussion of Test Results
6.1. Effect of reinforcement on crack depth measurements
Reinforcement is placed across in the middle of the beam that has been given artificial cracks. Reinforcement provided has a different effect for each crack depth. The reinforcement given gives different influences to each depth of crack. Test results in Table 4, Table 5 and Table 6 are the average value of the cracked depth of the 3 samples of concrete beams with 3 laying points as in Figure 6 for each variation of the tranducer distance which is then sought by the percentage of the value difference. The largest, smallest and average crack depth of the difference. The position of artificial crack depth based on three conditions i.e. the depth of crack is above the reinforcement, the depth of the crack is right in the position of the reinforcement and the depth of the crack that passes through the reinforcement. More details can be seen in the Figure 7 to 9 below.
This test is to find out how cracking depth measurement results when cracks are not going through the reinforcement, the cracks reach the position of the reinforcement and the cracks that pass through the reinforcement. The crack depth test for artificial crack depth is used in 3 concrete beam specimen, here are the results of the crack depth testing shown in the table and graphs below.

**Table 4.** The effect of Reinforcement on Crack Depth Measurement for artificial cracks depth 2 cm

| Specimens | Tranducer distance b (cm) | Crack Depth (H) |  | Correction value |
|-----------|--------------------------|-----------------|-----------------|-----------------|
|           |                          | H Measurement (cm) | H Artificial (cm) | Error relative (%) |                  |
| B.192     | 3                        | 2.789            | 2               | 39.4            | 0.717            |
|           | 6                        | 2.942            | 2               | 47.1            | 0.680            |
|           | 9                        | 2.633            | 2               | 31.7            | 0.759            |
|           | 12                       | 2.581            | 2               | 29.0            | 0.775            |
|           | Average                  | 2.736            | 2               | 36.8            | 0.733            |
|           | Standar Deviation         |                 |                 | 4.3             |                  |

**Figure 7.** Position of crack depth to reinforcement for artificial crack depth 2 cm.

**Figure 8.** Position of crack depth to reinforcement for artificial crack depth 4 cm.

**Figure 9.** Position of crack depth to reinforcement for artificial crack depth 6 cm.

**Figure 10.** Graph of Reinforcement Effect on Crack Depth Readings for artificial Crack Depths 2 cm.

\[ y = -0.0155x + 2.4846 \]

\[ R^2 = 0.6121 \]
The result above is the Test average of 3 specimen for each transducer distance variation. The results showed that the results of cracking depth measurement had greater results than the depth of artificial cracks due to the influence of reinforcement. **Figure 10** shows that the result of a crack depth measurement is above the artificial crack depth. Average relative error – the average for a 2 cm crack depth test is 36.8% with a relatively biggest error of 47.1% and the smallest 29%. The regression value for the reinforcement effect of the 2 cm artificial crack depth reading is $y = -0.0791x + 4.9083$ with a value of $R^2 = 0.2902$.

**Tabel 5.** The effect of Reinforcement on Crack Depth Measurement for depth of artificial cracks 4 cm

| Specimens | Transducer distance b (cm) | Crack Depth (H) | Error Relative (%) | Correction value |
|-----------|-----------------------------|------------------|--------------------|------------------|
|           |                             | Measurement (cm) | Artificial (cm)    |                  |
| B.194     | 3                           | 5.411            | 4                  | 35.3             | 0.739            |
|           | 6                           | 4.756            | 4                  | 18.9             | 0.841            |
|           | 9                           | 4.411            | 4                  | 10.3             | 0.907            |
|           | 12                          | 3.944            | 4                  | 1.4              | 1.014            |
| Average   |                             | 4.631            | 4                  | 16.5             | 0.875            |
| Standar Deviation |                             |                  |                    | 11.5             |

The average test of the 3 specimen described in **Table 5** has an average percentage of the realtive error of 16.46% with a percentage of the largest relative error of 35.3% and the percentage of the smallest realistic error of 1.4%. The results showed that the depth of measurement of cracks that reached the reinforcement has a greater result than the depth of artificial cracks due to the influence of the reinforcement. The regression value obtained is $y = -0.0791x + 4.9083$ with a value of $R^2 = 0.2902$. The factors that lead to the value of the test result greater than the depth of artificial crack are the wave speed at the reinforcement faster than the wave velocity in concrete [2]. Reinforcement causes the transmitted wave velocity to be greater so that the results of crack depth readings show greater results.

![Figure 11. Effect of Reinforcement Graph on crack depth readings for Artificial Crack Depth 4 cm.](image)
**Tabel 6. Effect of Reinforcement on Crack Depth Measurement for 6 cm depth of artificial cracks**

| Specimens | Tranducer distance b (cm) | H Measurement (cm) | H Artificial (cm) | Error relative (%) | Correction value |
|-----------|---------------------------|-------------------|------------------|--------------------|------------------|
| B.196     | 3                         | 5.858             | 6                | 2.369              | 1.024            |
|           | 6                         | 5.644             | 6                | 5.926              | 1.063            |
|           | 9                         | 5.722             | 6                | 4.630              | 1.049            |
|           | 12                        | 5.963             | 6                | 0.620              | 1.006            |
| Average   | 5.797                     | 6                 | 3.4              | 1.035              |
| Standar Deviation | 2.1                  |

The results of the test above indicate that the reading of the crack depth that passes through the reinforcement has a lesser outcome than artificial crack depth due to the influence of the reinforcement. The average percentage of the realistic error is 3.339% with the largest relative error percentage of 5.92% and a percentage of the smallest relative error 0.62%. The regression value for the reinforcement influence of the crack depth reading for a crack depth of 6 cm is \( y = 0.0056x + 5.865 \) with a value of \( R^2 = 0.4074 \). The factors resulting in the value of the test result smaller than the artificial crack's depth are the ultrasonic waves emitted by the Transmitter directly routed to the Receiver after the ultrasonic waves reach the reinforcement so that the wave Ultrasonic does not reach the base of artificial cracks i.e. at 6 cm depth.

**Figure 12.** Graph of Effect of Reinforcement on Crack Depth Measurement for Artificial Crack Depth 6 cm

6.2. Effective tranducer distance

Testing to determine the tranducer distance is effective using 4 distance variations between Tranducer (b) as described in Figure 13-16, namely 3, 6, 9 and 12 cm. Each variation of the tranducer distance used will be tested on 3 concrete beam samples for Each variation in depth of crack with 3 tranducer placement point as in Figure 6 which then sought the percentage value difference in the largest crack depth value, smallest and average percentage difference.
**Figure 13.** The position of the transducer for the value of b is 3 cm

**Figure 14.** The position of the transducer for the value of b is 6 cm

**Figure 15.** The position of the transducer for the value of b is 9 cm

**Figure 16.** The position of the transducer for the value of b is 12 cm

**Table 7.** Effect of Distance Variation on Crack Depth Measurement for artificial crack depth 2 cm

| Tranducer distance b (cm) | Specimens | H Measure (cm) | Error Relative (%) | Average of Error Relative (%) |
|--------------------------|-----------|----------------|--------------------|-----------------------------|
| 3                        | B192.01   | 2.500          | 25.00              | 39.44                       |
|                           | B192.02   | 3.200          | 60.00              |                             |
|                           | B192.03   | 2.667          | 33.33              |                             |
| 6                        | B192.01   | 2.950          | 47.50              |                             |
|                           | B192.02   | 3.221          | 61.06              |                             |
|                           | B192.03   | 2.654          | 32.69              |                             |
| 9                        | B192.01   | 3.033          | 51.67              |                             |
|                           | B192.02   | 2.767          | 38.33              |                             |
|                           | B192.03   | 2.100          | 31.67              |                             |
| 12                       | B192.01   | 3.133          | 56.67              |                             |
|                           | B192.02   | 2.833          | 41.67              |                             |
|                           | B192.03   | 1.7758         | 29.04              |                             |
Table 8. Effect of Distance Variation on Crack Depth Measurement for artificial crack depth 4 cm

| Specimens | H Measure (cm) | H Artificial(cm) | Error Relative (%) | Average of Error Relative (%) |
|-----------|----------------|------------------|--------------------|------------------------------|
| B194.01   | 4.967          | 4                | 24.17              | 35.28                        |
| B194.02   | 5.567          | 4                | 39.17              |                              |
| B194.03   | 5.700          | 4                | 42.50              |                              |
| B194.01   | 4.700          | 4                | 17.50              |                              |
| B194.02   | 4.400          | 4                | 10.00              | 18.89                        |
| B194.03   | 5.167          | 4                | 29.17              |                              |
| B194.01   | 4.367          | 4                | 9.17               |                              |
| B194.02   | 4.233          | 4                | 5.83               | 10.28                        |
| B194.03   | 4.633          | 4                | 15.83              |                              |
| B194.01   | 3.867          | 4                | 3.33               | 1.39                         |
| B194.02   | 3.733          | 4                | 6.67               |                              |
| B194.03   | 4.233          | 4                | 5.83               |                              |

Table 9. Effect of Distance Variation on Crack Depth Measurement for artificial crack depth 6 cm

| Specimens | H Measure (cm) | H Artificial(cm) | Error Relative (%) | Average of Error Relative (%) |
|-----------|----------------|------------------|--------------------|------------------------------|
| B196.01   | 6.140          | 6                | 2.338              | 2.369                        |
| B196.02   | 5.867          | 6                | 2.222              |                              |
| B196.03   | 5.567          | 6                | 7.222              |                              |
| B196.01   | 5.367          | 6                | 10.556             |                              |
| B196.02   | 5.800          | 6                | 3.333              | 5.926                        |
| B196.03   | 5.767          | 6                | 3.889              |                              |
| B196.01   | 5.933          | 6                | 1.111              |                              |
| B196.02   | 5.667          | 6                | 5.556              | 4.630                        |
| B196.03   | 5.567          | 6                | 7.222              |                              |
| B196.01   | 5.874          | 6                | 2.103              |                              |
| B196.02   | 6.137          | 6                | 2.279              | 0.623                        |
| B196.03   | 5.877          | 6                | 2.046              |                              |

Table 7-9 shows that the transducer distance is most effective and gives the readings closest to the depth of artificial crack that is at a distance of 12 cm with a relative percentage of average error of 14.6% or has an accuracy rate of 85.4%. The closer the transducer distance results in readings with a smaller level of accuracy. This result is approaching the provisions of BS 1881 [2] and Pundit Lab Operating Instruction [5] that the distance transducer effective to get the optimum test result is 15 cm.

7. Conclusion
The study concluded that the accuracy of the UPV testing results was influenced by reinforcement and distance transducer. The specimen with an artificial crack depth of ± 2 cm and ± 4 cm have a greater reading result with a relative error of 36.8% and 16.5%, while the test object with an artificial crack
depth of ± 6 cm has a smaller reading result with an error ± 3.4% relative. In addition, it obtained an effective transducer distance of 12 cm with a accuracy of 85.4%.

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