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Study to detect bond degradation in reinforced concrete beams using ultrasonic pulse velocity test method

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Abstract. Concrete technologists have used ultrasonic pulse velocity test for decades to evaluate the properties of concrete. However, the presented research work focuses on the use of ultrasonic pulse velocity test to study the degradation in steel-concrete bond subjected to increasing loading. A detailed experimental investigation was conducted by testing five identical beam specimens under increasing loading. The loading was increased from zero till failure in equal increments. From the experimentation, it was found that as the reinforced concrete beams were stressed from control unloaded condition till complete failure, the propagating ultrasonic wave velocity reduced. This reduction in wave velocity is attributed to the initiation, development, and propagation of internal cracking in the concrete surrounding the steel reinforcement. Using both direct and semidirect methods of testing, results of reduction in wave velocity with evidence of internal cracking at steel-concrete interface are presented. From the presented results and discussion, it can be concluded that the UPV test method can be successfully employed to identify zones of poor bonding along the length of reinforced concrete beam. The information gathered by such testing can be used by engineers for localizing repairs thereby leading to saving of time, labor and cost of repairs. Furthermore, the implementation strategy along with real-world challenges associated with the application of the proposed technique and area of future development have also been presented.

Keywords: ultrasonic pulse velocity test; bond evaluation; increasing loading; internal cracking; implementation strategy; real-world challenges

1. Introduction

Development of non-destructive testing technique (NDT) and evaluation methods have revolutionized the construction industry and opened new areas for materials technologists to explore. These methods are primarily used for structural health monitoring and to detect internal defects, thereby enabling engineers to quickly, effectively and economically examine and evaluate the performance of aging structures (Chang *et al.* 2003, Zhu and Rizzo 2013, Pavlopoulou *et al.* 2013, Sharma and Mukherjee 2015, Shih *et al.* 2013). According to ACI 228.2R (ACI 2013), NDT methods are most commonly utilized in the civil engineering field to control quality in new construction, condition assessment of existing structures, expediting the construction progress by in-situ testing and to assure the quality of the repair work. NDT techniques are broadly classified into five categories (Rehman *et al.* 2016) namely audio-visual inspection methods, stress wave methods, electro-magnetic methods, deterministic and infrared/ thermography/radiography methods. However, much recently research has been focused on the use of non-linear ultrasonic testing method which gained its popularity for its ability to allow better crack detection at early stages of damage (Daponte *et al.* 1995, Ongpeng *et al.* 2016, 2017, Shah *et al.* 2008, 2009). However the presented manuscript focuses on the use of traditional UPV method for detecting the degradation in steel-concrete bond of reinforced concrete beams. Jones (1948) developed ultrasonic tester in England, since the 1960s, the ultrasonic pulse velocity method has been applied in the laboratory and field investigation (Whitehurst 1966). Mutlib *et al.* (2016) and Malhotra (1976) presented an extensive list of application of UPV method for on-site investigations and structural health monitoring of buildings and bridges. Compressional, shear and surface wave a produced in an elastic solid when subjected to dynamic loading. Mandel *et al.* (2016) and Kaplan (1959) did experiments on concrete by changing the cement, aggregate and water ratios, their main target was to evaluate the effect of these changes on the relationship between UPV and compressive strength. They reported that type of cement had little to no effect on the pulse velocity and the use of rapid-hardening cement resulted in higher strength which led to faster pulse velocity. The factors influencing the wave speed can be categorized as size, grading, type and content of aggregate and cement, water-cement ratio, presence of additives, concrete age, curing condition, moisture content and temperature at testing, transducer contact, path length and the dimensions of the specimen, along with the stress level and presence of reinforcing steel.

Much research in the past has been focused on understanding the effect of each of these factors (Leslie and

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Cheesman 1949, Jones *et al.* 1969, Chao 2015, Selleck *et al.* 1998, Chung and Law 1983, Tahar *et al.* 2016, Umais *et al.* 2017). Similarly, the effect of aggressive environment such as freezing and thawing, fire exposure, alkali-silica reaction, sulfate exposure and corrosion of embedded steel reinforcement can also be identified using UPV test method and has been investigated in detail (Sounthararajan and Sivakumar 2012,Qasrawi and Marie 2013). Hamidian *et al.* (2011) investigated the influence of age, cement content, w/c ratio, and workability on high strength and light weight aggregate concrete and found UPV test as a powerful tool to assess the concrete strength and its quality.

The progressive deterioration of the structure can be documented and monitored by conducting repetitive testing at regular intervals on the same concrete elements. Furthermore, realizing the truly non-destructive nature of UPV test many researchers have used it to understand the internal structure of concrete by relating the pulse velocity to the strength gain, cement hydration and age of concrete (Qasrawi and Marie 2013, Woods and McLaughlin 1959, Whitehurst 1951, Cheesman 1949, Keating *et al.* 1989, Zongping *et al.* 2014). In-addition researchers have used UPV test method to investigate the effect of a variety of ingredients such as GGBFS, chloride intrusion and sodium hydrate on the compressive strength of concrete.

Saleem *et al.* (2016a, 2016b, 2010) successfully developed a non-destructive testing procedure to evaluate the load carrying capacity of anchor bolts by relating their pull-out strength to the Schmidt hammer rebound number. Furthermore, the authors proposed an analytical model to identify the influence of infill material properties on the load carrying capacity of anchor bars. However, based on the detailed literature review it is well known that the UPV method can be applied to reinforced concrete to detect internal defects such as presence of air voids, ill-alignment and internal cracking in the concrete surrounding the steel bars. Hence, it was envisioned to relate the ultrasonic pulse velocity to the presence of internal defects in the vicinity of concrete surrounding the steel reinforcement. This information would allow engineers/researchers to identify areas of weakness along the length of embedded steel and can lead to localized repairs resulting in saving of time, cost and labor. In this regards, the presented experimental research work details the innovative use of UPV test, by relating the reduction in pulse velocity to the initiation, development, and propagation of internal cracks at the steel-concrete interface and its surrounding, thereby allowing the identification of weak spots in bond along the length of steel reinforcement. The percentage reduction in ultrasonic pulse velocity owing to bond degradation is reported with respect to the unloaded condition which is referred to as control condition. Experimental results pertaining to both direct and semi direct methods of investigation are presented. In-addition the author has also outlined the practical approach for implementing the proposed technique in real-world situation and has also highlighted the challenges associated with its real-world application along with the areas of future development.

The proposed innovative approach can add a new dimension to the UPV testing method and can be used by field engineers as a stand-alone tool or in combination with other non-destructive test methods to judge the quality of bond of steel reinforcement. Furthermore, the data generated by employing the proposed method can be used to increase the confidence level in on-site judgments of field engineers.

2. Objectives

The research work aims to focus on developing a new innovative method of use of ultrasonic pulse velocity test. The main objectives of the presented research are summarized as below:

1) To develop experimental proof of concept that ultrasonic pulse velocity can be related to the quality of bond of reinforcing steel bar embedded in concrete.

2) To provide experimental evidence that the reduction in pulse velocity owing to increase in loading is attributed to initiation, development and propagation of internal cracking of concrete in the vicinity of reinforcing steel bar.

3) Understanding the various challenges associated with the real world application of proposed method and to shed light for future development of the suggested technique.

3. Materials and testing

Fig. 1(a) depicts the mold used for casting eight reinforced concrete beam specimens having a cross-section of 100×150×500 mm along with six cylindrical specimens having 100 mm Φ and 200 mm high. Three beam specimens were casted to determine the maximum load carrying capacity for the beam elements and the concrete cylinders were used for concrete compressive strength testing. All the concreting was done, using Type I - ordinary Portland cement (OPC) having a specific gravity of 3.15 and conforming to ASTM C150. The chemical composition of OPC by weight (%) was as follows: CaO=64.3, SiO_2=22, Al_2O_3=5.64, Fe_2O_3=3.8, MgO=2.11, Others=2.15. Desert sand was used as fine aggregate possessing bulk specific gravity and water absorption of respectively, 2.66 and 0.60%. Broken limestone was used as coarse aggregate having bulk specific gravity and water absorption of 2.45 and 2.05%, respectively. The maximum size of coarse aggregate was 19 mm and its grading requirement was in conformity with ASTM C33. The concrete mixture was prepared using water to cement ratio of 0.4 by mass, the cementitious material content of 350 kg/m^3, fine to the coarse aggregate ratio of 0.667 by mass and slump was 100 mm using polycarboxylate ether superplasticizer.

A single deformed steel reinforcing bar with a diameter of 16 mm and length of 495 mm, as shown in Fig. 1(b), was embedded in the concrete beam having a bottom cover of 50 mm, 2.5 mm clearance was allowed from each end of the mold for ease in steel bar placement. ASTM C192 was followed to ensure standard practice for casting and curing of concrete specimens under laboratory conditions. After

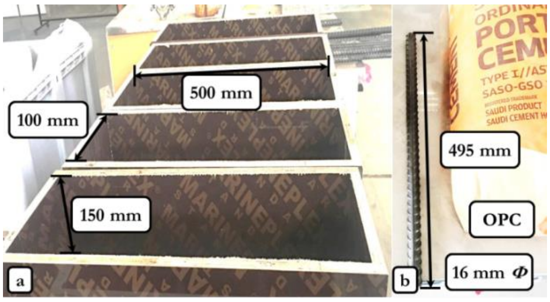

Fig. 1 (a) Molds (b) Steel Rebar & OPC

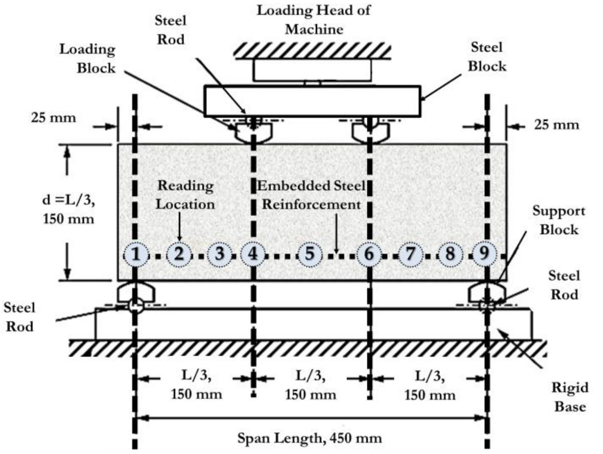

Fig. 2 Schematic diagram of test setup

the desired curing period of 28 days, the compressive strength was performed through Compression Testing Machine (CTM) on six concrete cylinders with 100 mm diameter and 200 mm height, as per ASTM C 39. Uniform axial compressive load was applied until failure of the specimen to get the compressive strength. The average of the six cylindrical specimens was found to be 34.10 MPa while the coefficient of variation among each test specimen was 1.85% which is within the acceptable limit of 3.2%.

Flexural load capacity of reinforced concrete beams was measured using a four-point loading method (also known as third-point loading method). The rationale for choosing a four-point loading method in place of three point loading method was based on its ability to create a pure bending zone allowing for vertical crack propagation. This led to the creation of tension zone at the bottom of the beam and a compression zone at the top portion of the beam allowing researchers to closely monitor; record and evaluate the initiation, development and propagation of cracking in the prescribed zone. In effect, during experimentation the research team was successfully able to observe reduction in wave velocity owing to development of internal cracking. This allowed for the identification of locations of bond degeneration/degradation along the length of steel reinforcement. Fig. 2 depicts the schematic diagram of the four point loading test used for the experimental investigation. Each beam had a single reinforcing steel bar embedded in the middle. Ultrasonic pulse velocity readings were recorded at each location along the length of reinforcement. This allowed for accurate estimation of weak spots along the length of reinforced concrete beam. First,

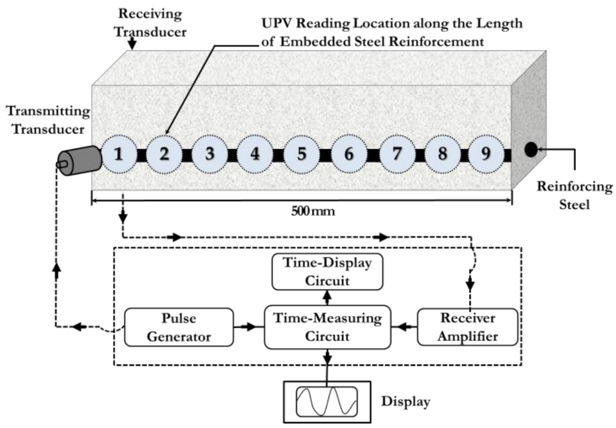

Fig. 3 Schematic diagram of UPV test

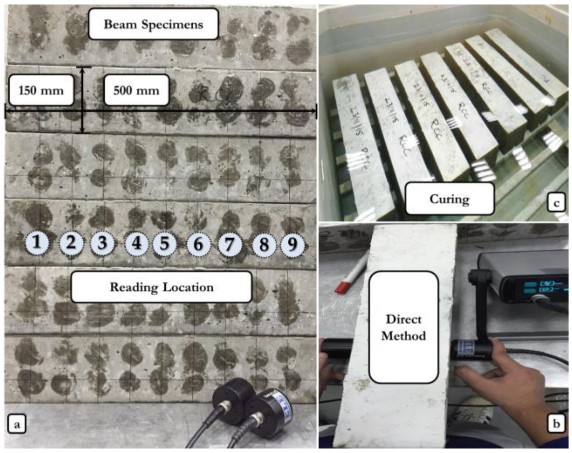

Fig. 4 (a) Beam samples depicting the reading locations along the length of reinforced concrete beam (b) Direct method of testing (c) Curing of beam specimens

the UPV readings were recorded for all beams prior to the application of loading. This stage is referred from here onwards as the control condition for the testing. The values of ultrasonic pulse velocity recorded under the control condition served as the benchmark for the further testing.

Fig. 3 presents the schematic view of ultrasonic pulse velocity testing protocol while Fig. 4 depicts the real world application of the schematic view. Nine locations marked along the length of steel reinforcement and UPV readings were recorded at each location using direct and semidirect method of testing in accordance with ASTM C597. Three of the eight beam specimens were used for strength testing under four point loading test in accordance with ASTM C 78. The objective of this procedure was to establish an average value of maximum load carrying capacity for the identical beam specimens. The average load carrying capacity of the three identical beam specimens served as a benchmark value of P_{max}. The P_{max} value was used for all further testing and loading on the remaining five beam samples was applied in equal increasing load increments. In favor of increasing the readability of the manuscript only 25% incremental loading values are reported here, however, the ultrasonic pulse velocity values were recorded after every 10% increment in loading. Since the general trend of reduction in wave velocity with an increase in applied loading is the same, hence the decision of reporting 25% increment in loading is justified. However, it is to be brought to reader's attention that the initiation of cracking in the vicinity of concrete surrounding the steel reinforcement was noticed at 10% loading; afterward the velocity continued to decrease resulting in its lowest value at P_{max}.

The average P_{max} for three beam specimens was recorded as 60.3 KN. The UPV readings are reported here, after the application of 25% of P_{max} at 15.1 KN, 50% of P_{max} at 30.15 KN, 75% of P_{max} at 45.23 KN and finally after P_{max}.

Fig. 4 presents the experimental investigation protocol. The transducer and receiver were firmly coupled at the opposite ends of the specimen; petroleum jelly was used for coupling between the transducer and the specimen. The velocity was calculated by measuring time, in microseconds (μs), that the ultrasonic pulse took to the pass through the known distance of specimen. The wave velocity was obtained in *m/s*, by dividing the path length with the time taken for wave propagation (Cheesman 1949). For ordinary strength concrete, based on the dimensions of the specimen and the maximum aggregate size (19 mm) the frequency of the transducer was chosen as 54 kHz with a wavelength of about 68 mm in accordance with BS 1881 (1986) and RILEM (1972). Prior to testing, it was ensured that the equipment is calibrated with the help of reference bar and there are no air pockets in contact between the transducers and the concrete surface. UPV readings were recorded at least five times on each location marked along the length of the reinforced concrete beam. However, the minimum time taken for the ultrasonic pulse to arrive at the receiving transducer is reported in the results of the presented manuscript (BS 1986, Tarun *et al.* 2004).

The rationale behind the choosing the fastest transmit time instead of mean time along with standard deviation was based on the logic that since the transmit time of the ultrasonic pulse is effected by proper coupling of the transducer and the receiver, along with pressure exerted on these components. Therefore, for the same location the fastest transmit time would occur under best possible coupling. Hence, in order minimize human error the decision of choosing the fastest time has logical backing.

4. Ultrasonic pulse velocity testing

All the testing conducted for the presented manuscript was done in accordance with ASTM C597 (2003). The sample dimensions, frequency, maximum size of aggregate, temperature, moisture and curing conditions of concrete, path length, age of concrete at testing, transducer contact and presence of steel reinforcement perpendicular to the propagation path of wave were all taken into consideration and were controlled in accordance BS 1881 (BS 1986, Tarun *et al.* 2004). Correction factor of 0.975 related to the presence of 16 mm Φ diameter steel bar perpendicular to the propagation path of ultrasonic wave was applied to the reported reading in the manuscript. Furthermore, all the testing was conducted on air dried samples after 28 days of curing in an air-conditioned laboratory with a temperature of 20±3°C. Proper coupling and pressure was applied on the transducers to ensure stable transit times, the strength and the shape of the signal was monitored viewing the shape and magnitude of received waveform and only sinusoidal shape of the waveform were recorded.

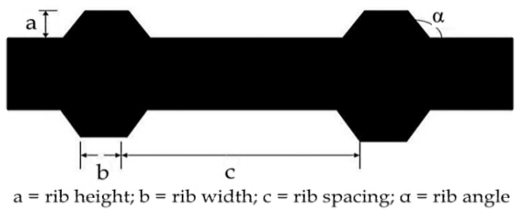

Fig. 5 Schematic diagram of steel reinforcement depicting the parameters affecting bond

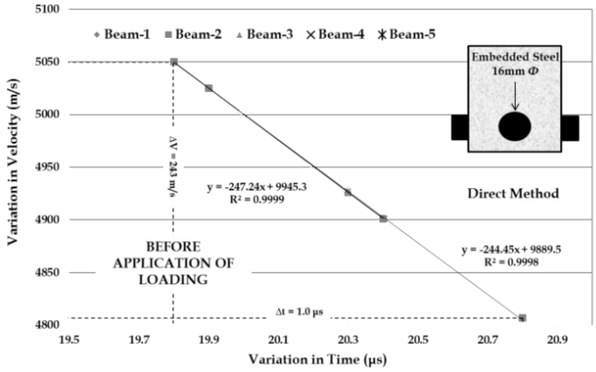

Fig. 6 Range of velocity and time under control condition

In-addition, the factors affecting the bond behavior of steel embedded in concrete were also thoroughly taken into consideration and much attention was paid to the mechanism of bond development. These factors include reinforcing bar size, cover to reinforcement, bar profile such as rib height, rib angle, a/c ratio, conditions of concrete and the exposure conditions. Fig. 5 depicts a schematic diagram representing the mechanical factors affecting the bond development and failure mechanics. In the presented study, the author envisioned to induce a splitting type of failure. In this regards the mechanical parameters of the steel reinforcement were chosen such that splitting type of bond failure is preferred. Hence a, which represents the rib height was chosen to be less than $0.05d$ and $0.1c$, $\propto$ representing the rib angle was chosen to be less than 45^o, b represents the rib width and c represents the rib spacing. The bar selected had small rib height and largely spaced ribs with low angle.

Splitting type of failure was chosen based on the rational that since the fundamental objective of the presented study is to provide proof of concept that by inducing cracks in the vicinity of embedded steel reinforcement, the velocity of the ultrasonic wave will reduce. In this regards, the splitting type of failure was favorable in comparison to the pull-out type of failure mechanism. Furthermore, much effort and attention was paid to produce a consistent quality of concrete. The reasoning behind this effort was to have uniformity in the bonding quality along the length of embedded reinforcement there by lowering the variation among the control condition as shown in result presented in Fig. 6.

Table 1 UPV readings before the application of loading (control condition)

Read. Loc.	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)
	Beam-1$^{\Xi}$		Beam-2$^{\Xi}$		Beam-3$^{\Xi}$		Beam-4$^{\Xi}$		Beam-5$^{\Xi}$	
1	20.8	4807	19.9	5025	19.9	5025	20.2	4950	20.3	4926
2	19.9	5025	19.9	5025	20.3	4926	20	5000	19.9	5025
3	19.9	5025	20.4	4901	19.9	5025	20.3	4926	19.8	5050
4	20.4	4901	19.9	5025	19.8	5050	20	5000	19.9	5025
5	20.4	4901	20.4	4901	20.3	4926	20.4	4901	19.8	5050
6	20.4	4901	19.9	5025	19.9	5025	20.3	4926	20.4	4901
7	20.3	4926	19.8	5050	19.8	5050	20.4	4901	19.9	5025
8	20.3	4926	20.8	4807	19.9	5025	19.8	5050	20.3	4928
9	20.4	4901	19.8	5050	19.9	5025	20.3	4926	20.4	4901

$^{\Xi}$ The data provided in the table represents the lowest time (*μs*) reading and the corresponding fastest wave velocity (*m/s*), recorded using direct method of testing.

Table 2 UPV readings after the application of loading (direct method)

Read. Loc.	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)	T (*μs*)	V (*m/s*)
	0.25 P_{max}^{Ξ}		0.50 P_{max}^{Ξ}		0.75 P_{max}^{Ξ}		P_{max}^{Ξ}	
1	26.8	3731	26.9	3717	27.6	3659	29.1	3412
2	26.8	3684	27.5	3636	28.8	3539	30.1	3254
3	27.3	3649	27.7	3597	27.9	3639	30.9	3169
4	27.8	3533	28.7	3497	29.5	3421	31.9	3010
5	29.1	3333	28.7	3210	32.5	3005	33.3	2806
6	28.2	3533	29.5	3389	30.3	3331	31.5	3122
7	27.4	3636	27.8	3597	28.7	3551	29.9	3322
8	27.8	3584	27.3	3663	27.7	3652	28.7	3460
9	26.2	3797	27.4	3649	28.7	3505	28.1	3533

$^{\Xi}$ The data provided in the table represents the reduction in wave velocity (*m/s*) with the increase in applied loading using direct method of testing.

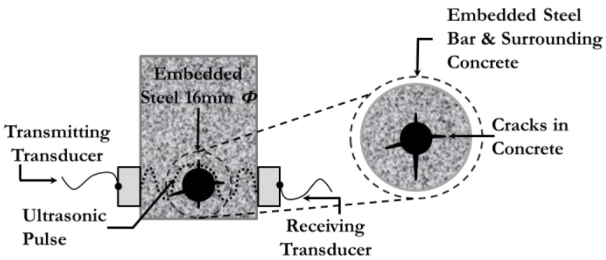

Fig. 7 Conceptual diagram depicting the presence of internal cracking

5. Results and discussion

The first step related to experimentation was to establish a benchmark value of ultrasonic pulse velocity. In order to achieve this target, firstly all five beam samples were tested along the length of the reinforcing steel bar. Care was taken to ensure proper coupling and a minimum of five readings were recorded at each location using direct method of investigation. Table 1 presents the reading of ultrasonic pulse velocity test prior to application of loading; this condition is referred here onwards as the control condition. The control condition readings served as a benchmark and all further reduction in the velocity of ultrasonic wave was reported with reference to the control condition.

Fig. 6 depicts the velocity with respect to time for the control condition using the direct method of investigation.

The vertical axis represents the velocity of ultrasonic wave and the horizontal axis is the corresponding time range. The objective of presenting this result to the readers is to highlight the quality and uniformity of concrete beams. It can be seen that the maximum variation in the time for wave propagation is 1 *μs*, furthermore, the maximum wave velocity is about 5000 *m/s*, which indicates a good quality of concrete and a perfect bond condition for the embedded steel reinforcement. These beam specimens were further loaded in equal increments of 10% of P_{max} till failure and reduction in ultrasonic pulse velocity was recorded.

The preceding results depict the findings of the detailed experimental investigation. Fig. 7 shows the schematic conceptual diagram detailing the presence of internal cracking, degradation and non-uniformity in the concrete surrounding the steel reinforcement subjected to increasing loading. Using both direct and semidirect method of evaluation, it is possible to judge the reduction in the ultrasonic wave velocity, this gives practicing engineers an indication about the bond quality of reinforcing steel, thereby adding a new dimension to the non-destructive testing method.

5.1 Direct method

The results provided the proceeding section details the findings of an experimental investigation conducted using the direct method of testing using ultrasonic pulse velocity test. Nine locations were marked along the length of the concrete beam, transmitting and receiving transducers were placed on the opposite sides of the concrete beam and shortest time taken by the ultrasonic pulse to transit 100 mm path length was recorded. Since the ultrasonic pulse velocity is 1.4 to 1.7 times faster in steel as compared to concrete, reduction factor of 0.975 related to the presence of a single steel reinforcement perpendicular to the path of wave travel was applied on the reading. The reduction factor was chosen based on L_s/L of 1/7 corresponding to very good quality concrete with V_s of 5000 m/s in accordance with BS 1881 (1986). Furthermore, testing was conducted on an air dried sample in a temperature control environment of 20±3℃, hence in accordance with BS 1881 no temperature correction was applied.

Table 2 presents the reading for the beam members after the application of loading, the reported loading increments are in equal intervals of 25% of P_{max}. This value was chosen in favor of keeping the readers interest. Fig. 8 presents the variation in the ultrasonic pulse velocity along the length to the embedded steel reinforcement after the application of loading. It can be seen from the results that there exists a clear reduction in ultrasonic pulse velocity with increase in loading. As the loading is increased the reduction is wave velocity increases. This is a clear indication of the presence of internal cracking at the concrete and steel interface,

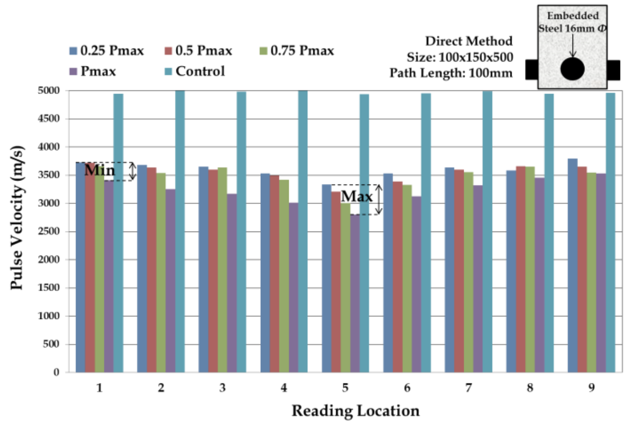

Fig. 8 Variation in pulse velocity along the length of reinforced concrete beam (direct method)

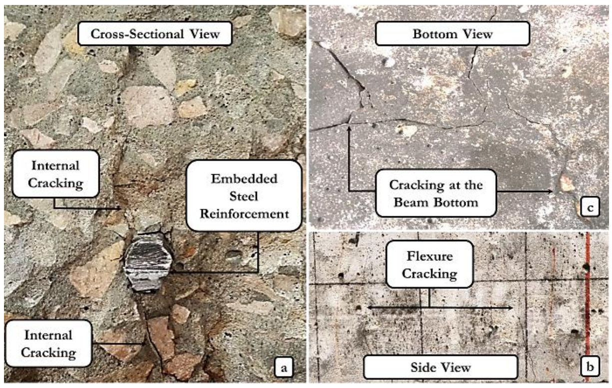

Fig. 9 Experimental evidence of internal cracking in the concrete surrounding the steel reinforcement (a) Cross-sectional view (b) Side view (c) Bottom view

resulting in degradation of the bond of reinforcing steel bar. From Fig. 8 it is further noticed that the reduction in velocity maximizes in the middle location of the beam member this is because the middle portion of the reinforced concrete beam is subjected to pure bending resulting in vertical cracking which result in maximum degradation of bond.

Fig. 9 presents the experimental proof of internal cracking at the concrete-steel interface. From the cross-sectional view it is evident that cracking initiated at the interface of steel and concrete and propagated in the vicinity of concrete surrounding the steel reinforcement. Fig. 9 also presents the side view and the bottom view of cracking resulting from the application loading. Hence it can be said that the reduction in ultrasonic pulse velocity is owing to the initiation, development and propagation of internal cracking at the steel-concrete interface which led to degradation of bond of reinforcing steel bar. Fig. 10 presents the reduction of ultrasonic wave velocity (*m/s*) and the corresponding increase in wave transit time (μs) after the application of loading. It can be seen from the result that as the applied loading increases the ultrasonic pulse velocity reduces and the corresponding wave transit time increases. Furthermore, range of the reduction in wave velocity and increase in transit time is also displayed on the result. Fig. 11 and Table 3 present the percentage reduction in velocity

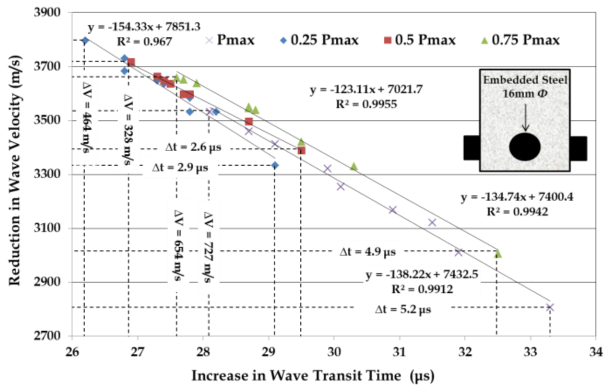

Fig. 10 Reduction in pulse velocity with increase in applied loading (direct method)

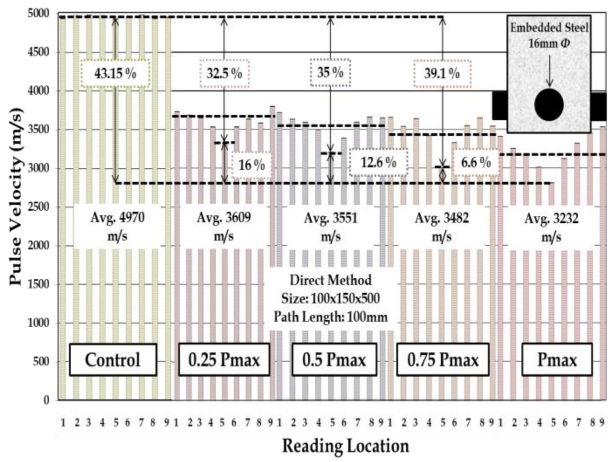

Fig. 11 Reduction in pulse velocity along the length of reinforced concrete beam with increase in applied loading in comparison to control condition (direct method)

Table 3 Percentage reduction in wave velocity with respect to the control condition (direct method)

Loading Range (%)	Range of Pulse Velocity (*m/s*)		Reduction in Velo. (*m/s*)	% age Reduction w.r.t Control (%)	%age Reduction w.r.t P_{max} (%)
Control	5001	4936	65	-	43.15
0~25	3797	3333	464	32.48	15.81
25~50	3717	3210	328	34.97	12.59
50~75	3659	3005	654	39.12	6.62
P_{max}	3533	2806	727	43.15	-

for each loading increment. It can be seen that there is 32.5%, 35%, 39.1% and 43% reduction in ultrasonic pulse velocity with respect to the control condition with increase in loading up to 25% of P_{max}, 50% of P_{max}, 75% of P_{max} and P_{max} respectively. By analyzing the results presented in Fig. 8, 9, 10 and 11 it can be concluded with certainty that the increase in loading results in the development of internal cracking at the steel-concrete interface, resulting in degradation of bond. This degradation of bond can be identified as reduction in ultrasonic wave velocity.

Furthermore, by analyzing result presented in Fig. 8 it can be concluded that the using the proposed method of investigation it is possible to identify location of maximum

Table 4 UPV readings after the application of loading (semidirect method)

Read. Loc.	T (μs)	V (m/s)	T (μs)	V (m/s)	T (μs)	V (m/s)	T (μs)	V (m/s)
	0.25 P_{max} Ξ		0.50 P_{max} Ξ		0.75 P_{max} Ξ		P_{max} Ξ	
1	24.10	3361	25.20	3271	26.25	3111	27.70	2949
2	25.82	3161	26.60	3057	26.20	3101	29.70	2668
3	26.86	2986	27.40	2950	27.59	2900	30.50	2600
4	27.20	2931	28.00	2826	28.60	2778	30.50	2578
5	27.83	2831	28.80	2775	28.91	2720	30.70	2555
6	26.65	3000	27.81	2896	27.98	2821	30.43	2589
7	25.49	3161	26.29	3101	26.74	3001	28.72	2771
8	25.71	3146	26.00	3161	26.26	3100	27.10	2999
9	23.80	3437	24.60	3353	25.90	3161	26.80	3043

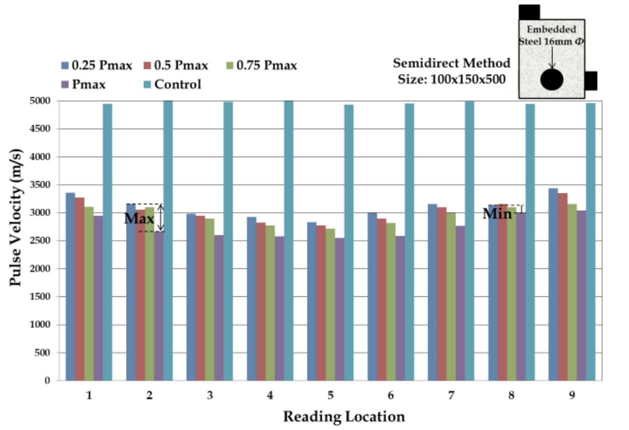

Fig. 12 Variation in pulse velocity along the length of reinforced concrete beam (semidirect method)

bond degradation i.e., weak spots along the length of reinforced concrete beam. This information can be used by practicing engineers to identify areas for detailed investigation and can also be used to identify areas where critical strengthening and repair might be needed. This can lead to increase in efficiency and reduction in cost of repairs for reinforced concrete members.

5.2 Semidirect method

After the completion of direct method of investigation, a conscious decision was made to apply the semidirect method of investigation. This decision was taken based on the rational that any variance in the two methods would highlight the short comings in the proposed technique. Furthermore, the presence of evidence produced by the application of semidirect method would further strengthen the proposed claims. Hence, the proceeding section details the experimental findings using the semidirect method of investigation. Table 4 presents the ultrasonic pulse velocity reading values after the application of loading using semidirect method. A minimum of five readings were taken at each location along the length of the reinforced concrete beam, with transmitting transducer placed on top of the beam element while the receiving transducer was placed on the side of the beam element. The reported readings correspond to the shortest time and the fastest velocity.

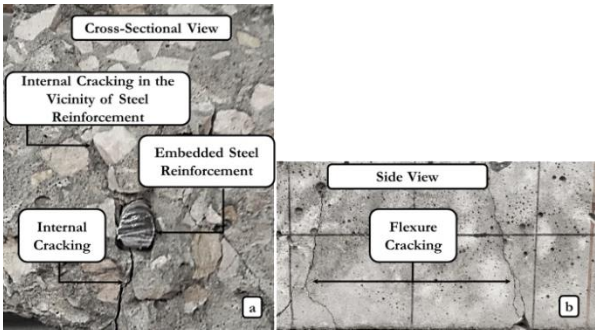

Fig. 13 Experimental evidence of internal cracking at the steel-concrete interface (a) Cross-sectional view (b) side view

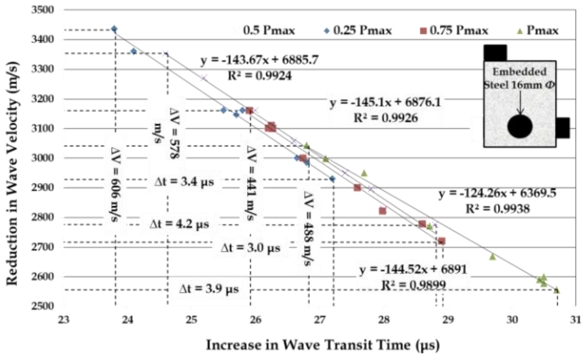

Fig. 14 Reduction in pulse velocity with increase in applied loading (semidirect method)

Fig. 12 presents the result of variation in ultrasonic pulse velocity measured after the application of loading increments using semidirect method, along the length of reinforced concrete beam. From the presented result it is clear that as the applied loading increases the ultrasonic pulse velocity reduces, furthermore it is evident from the result that the location of maximum bond degradation can be identified by comparing the reduction in wave velocity. One difference that was found from the comparison of semideirect and direct method was that the values in the pure bending zone i.e., location 4, 5 and 6 remained constant in semidirect method whilst in the direct method there was slight variation among these readings. This phenomenon could be attributed to the internal path taken by the wave to travel through the reinforced concrete. Fig. 13(a) presents the experimental evidence of the existence of internal cracking at the interface of steel and concrete while 13(b) displays the vertical cracking on the side of the beam in the pure bending zone. The presence of these cracks coupled with the reduction in pulse velocity indicates the degradation in the bond of embedded steel reinforcement. Fig. 14 depicts the reduction in velocity and corresponding increase in ultrasonic pulse transit time after each increment in loading. From the presented result it is evident that as the applied load increases the internal cracks at the steel-concrete interface develop, resulting in degradation of bond. This leads to reduction in the ultrasonic pulse velocity for the same path length. Furthermore, the range of reduction in pulse velocity along with increase in transit time is also displayed in the presented result.

Table 5 Percentage reduction in wave velocity with respect to the control condition (semidirect method)

Loading Range (%)	Range of Pulse Velocity (*m/s*)		Reduction in Velo. (*m/s*)	% age Reduction w.r.t Control (%)	%age Reduction w.r.t P_{max} (%)
Control	5001	4936	65	-	48.24
0~25	3437	2831	606	42.65	9.75
25~50	3353	2775	578	43.78	7.93
50~75	3161	2720	441	44.89	6.07
P_{max}	3043	2555	488	48.24	-

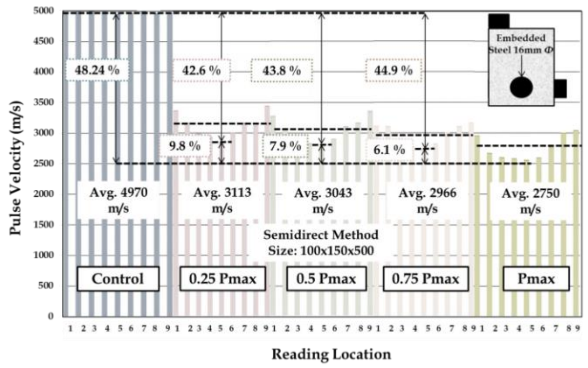

Fig. 15 Reduction in pulse velocity reading along the length of reinforced concrete beam with increase in applied loading in comparison to control condition (semidirect method)

Table 5 and Fig. 15 present the comparison of reduction in ultrasonic pulse velocity after the application of loading for various increments. It can be seen that there is 42.6%, 43.8%, 44.9% and 48.24% reduction in ultrasonic pulse velocity with respect to the control condition with increase in loading from 25% of $P_{max,}$ 50% of P_{max}, 75% of P_{max} and P_{max} respectively. By analyzing the results presented in Fig. 12, 13, 14 and 15 it can be concluded with certainty that the increase in loading results in the development of internal cracking at the steel-concrete interface, resulting in degradation of bond. This degradation of bond can be identified as reduction in ultrasonic wave velocity. Furthermore, by analyzing result presented in Fig. 12 it can be concluded that using the proposed method of investigation adds a new dimension to ultrasonic pulse velocity testing, thereby allowing engineers to identify critical areas along the length of reinforced concrete members. The information gathered from the proposed technique can be used for localized strengthening, thereby making the field investigation more efficient, increasing the reliability/confidence level of engineers and reducing the cost of repair and maintenance.

6. Implementation strategy & real world challenges

One of the fundamental challenges for any new method of non-destructive investigation is its ease of application in real world situation. In this regards the following section details the implementation strategy of the proposed method along with highlighting various real world challenges associated with its implementation. The objective of the author is to convey to the readers, various challenges that can be encountered in real world situations.

The researcher plans to propose and develop an innovative use of UPV test method that can reduce the cost of maintenance while being least labor-intensive. In this regards the author proposes that prior to any field testing the visiting team should conduct a preliminary investigation survey to identify challenges associated with the job and should study the structural drawings. Since the proposed innovation is designed for the engineers and trained lab technicians, they should identify environmental condition, nature of the structure, its type and condition. After highlighting critical areas for testing, a grid pattern can be marked on the surface of the reinforced concrete element. UPV test can be used to take readings at each grid location. Later-on these readings can be analyzed to evaluate the internal bond condition of the zone. The size and spacing of the grid will be governed by size of the reinforced concrete element. Furthermore, the proposed technique can be used in conjunction with other non-destructive testing methods to increase the result reliability and cross-checking. This combination of NDT techniques will boost the confidence of testing team and help in narrowing down the location which requires detailed testing. In-addition, based on the site situation, the structural element can be subdivided into segments. This strategy can yield the maximum useful and reliable data while being economical and least laborious.

For remote monitoring operations engineers utilize a variety of sensors placed at strategic locations to monitor the health of the structures e.g. for large bridge structures remote monitoring operation utilizes sensors, data recorders, indicators to record and report localized data. This data is analyzed to visualize the overall performance of the structure. In this regards the presented method has the advantage that it can be used to critically investigate key locations and can also be used as a tool to identify problematic areas.

One of the most important challange pertaining to real-world implementation of the proposed technique is the ability to identify the areas where the detailed critical investigation is needed especially in cases where there exist no blueprints/structural drawings. In such as situation the use of single test method is not advisable and the field testing engineers should identify areas of critical importance by combining the proposed technique with rebar scanners to gain the confidence level regarding the onsite data. By using this strategy, critical locations can be identified leading to an effective and efficient field investigation.

7. Conclusions

An experimental study to evaluate the bond of reinforcing steel bar embedded in concrete has been presented. The focus of the study was to present experimental evidence relating the reduction in pulse velocity to the presence of internal interfacial cracking in the concrete surrounding the steel reinforcement. Experimental evidence related to both direct and semidirect methods has been presented. From the presented results and discussion following conclusions can be drawn:

- Using both direct and semidirect UPV testing methods, weak bond spots along the length of steel reinforcement can be successfully identified.
- The ultrasonic wave velocity reduces with the degradation in bond. Using direct method of investigation it was observed that there is 32.5%, 35%, 39.1% and 43% reduction in ultrasonic pulse velocity with respect to the control condition with increase in loading to 25% of P_{max}, 50% of P_{max}, 75% of P_{max} and P_{max} respectively.
- Using semidirect method of investigation it was observed that there is 42.6%, 43.8%, 44.9% and 48.24% reduction in ultrasonic pulse velocity with respect to the control condition with increase in loading to 25% of P_{max}, 50% of P_{max}, 75% of P_{max} and P_{max} respectively. The increase in percentage reduction is attributed to increased path length for semidirect method.

The presented work details an innovative new approach to use the ultrasonic pulse velocity method for bond quality evaluation. Its application and combined use with other non-destructive testing methods can add a new dimension to the ultrasonic pulse velocity testing.

8. Range of application

The presented manuscript details an experimental method which related the ultrasonic pulse velocity to the degradation of bond of embedded steel reinforcement. This type of evaluation can potentially lead to a new class of non-destructive on-filed evaluation. Furthermore, the information provided by the proposed technique can be used to identify weak areas along the length of reinforced concrete member. This knowledge can lead to precise zone-wise strengthening of the RC members thereby resulting in saving of time, minimizing the repair and maintenance cost. However, it is to be brought to the reader's attention that the implementation of any method in real world situation requires a large data bank of reliable literature. Hence, the proposed method needs to be tested on a large variety of situations, real-world scenarios to increase the confidence level. The results presented in the research work provide validity to the claim that the ultra-sonic pulse velocity test can be used to judge the quality of bond between the reinforcing steel bar and surrounding concrete. The presented results are valid for reinforced concrete beam specimens with dimensions of 100×150×500 mm having a single 16 mm Φ steel reinforcing bar embedded in normal strength concrete. The quality of concrete-steel interface plays a vital role in the transit time for ultra-sonic pulse.

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