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Development of non-destructive testing method to evaluate the bond quality of reinforced concrete beam

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Abstract. Non-destructive tests are commonly used in construction industry to access the quality and strength of concrete. However, till date there is no non-destructive testing method that can be adopted to evaluate the bond condition of reinforced concrete beams. In this regard, the presented research work details the use of ultra-sonic pulse velocity test method to evaluate the bond condition of reinforced concrete beam. A detailed experimental research was conducted by testing four identical reinforced concrete beam samples. The samples were loaded in equal increments till failure and ultra-sonic pulse velocity readings were recorded along the length of the beam element. It was observed from experimentation that as the cracks developed in the sample, the ultra-sonic wave velocity reduced for the same path length. This reduction in wave velocity was used to identify the initiation, development and propagation of internal micro-cracks along the length of reinforcement. Using the developed experimental methodology, researchers were able to identify weak spots in bond along the length of the specimen. The proposed method can be adopted by engineers to access the quality of bond for steel reinforcement in beam members. This allows engineers to carryout localized repairs thereby resulting in reduction of time, cost and labor needed for strengthening. Furthermore, the methodology to apply the proposed technique in real-world along with various challenges associated with its application have also been highlighted.

Keywords: ultra-sonic pulse velocity test; bond assessment; incremental loading; micro-crack development; internal crack propagation; real-world application strategy

1. Introduction

Non-destructive tests (NDT) allow engineers and researchers to evaluate the condition of a sample without causing permanent damage. NDT is commonly used in construction industry to access the quality and strength of concrete specimens. Much research work has been conducted in the past for the development of non-destructive tests. However, the primary focus of the past research work has been the application of the test methods for onsite condition assessment. Ishibashi *et al.* 2009, 2004 conducted a detailed study on the various strengthening techniques that were adopted across Japanese railway network to protect the infrastructure against earthquake loading. Nishimura *et al.* 2004 provided a detailed damage assessment of the railway infrastructure in Japan caused by earthquake loading. Among the various assessment tools available to engineers there is a distinct lack of non-destructive tests for evaluating the bond condition of reinforced concrete members. Rehman *et al.* 2016 provided a comprehensive review of the non-destructive testing methods based on the earlier work by Hoła *et al.* 2010, Ishibashi *et al.* 2004, Rens *et al.* 1997, Chang *et al.* 2003, Ohtsu *et al.* 2002, the researcher categorized non-destructive testing techniques into five main classes such as audio-visual techniques, electro-magnetic methods, stress wave techniques, infrared and thermographic evaluation methods. Among the presented techniques ultra-sonic pulse velocity test method gained notoriety for its versatility to be applied in both early age crack detection and long-term monitoring capability. Recently, owing to the need for early crack detection non-linear form of ultra-sonic pulse velocity (UPV) test gained popularity among researchers as it allows for better crack detection at early age of strength development (Ongpeng *et al.* 2016, 2017, Shah *et al.* 2008, 2009). However, the objective of the presented manuscript is the use of traditional UPV test for bond quality assessment of reinforced concrete beams. The rationale behind using the traditional test as compared to the new non-linear method is the availability of factors used for wave degradation owing the presence of multiple steel reinforcement bars along the propagation path of ultra-sonic wave. Furthermore, the wealth of data available for the traditional UPV test is much greater as compared to the new non-linear method which makes enhancement to traditional method more useful for the larger researcher/engineering community.

Euichul *et al.* 2018, Sharma *et al.* 2015, Mutlib *et al.* 2016 and Mandel *et al.* 2016 utilized non-destructive tests such as ultra-sonic pulse velocity test for quick and effective on-site structural health examination of bridges and large buildings. Researchers investigated the effect of varying cement content, aggregate type, and water-to-cement ratio on ultra-sonic pulse velocity with regards to

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compressive strength. From experimentation researchers reported that the cement type had negligible effect on the wave velocity, however, aggregate size, its grading, water cement ratio, age of concrete, presences of additives and temperature of testing influenced the UPV results. Furthermore, factors such as presence of steel reinforcement along or perpendicular to the propagation path of ultra-sonic pulse, loading condition, transducer contact and path length had a significant effect on the UPV test. Bayran *et al.* 2014, Taher *et al.* 2016, Chao *et al.* 2015 investigated the strength and bond stress-slip behavior using ultra-sonic pulse velocity test. Qasrawi *et al.* 2013, Terkin *et al.* 2014 investigated the strength properties of cemented paste using ultra-sonic pulse velocity tests and reported that UPV test is an immensely useful method to judge the quality and strength of concrete. Zongping *et al.* 2014 investigated the shape steel embedded in recycled aggregate concrete and its effects on corrosion of steel reinforcement. Kamaya *et al.* 2007, 2003, Sharon *et al.* 1995 and Saiidi *et al.* 2006, 2007, presented the crack propagation model taking into consideration multiple crack growth and their interaction with each other. Saleem *et al.* 2010 also developed an analytical model for crack propagation in an anchor-infill assembly along with infill material properties that allow engineers to predict and control crack propagation. Researchers reported that by employing UPV testing in periodic cycles it is possible to access the degradation in strength and quality of concrete. Furthermore, this kind of investigation would allow engineers to identify weak areas or areas of progressive deterioration thereby leading to localization of damaged zones in concrete members.

Saleem *et al.* (2016a, b, 2017, 2018a, b, c) successfully developed an innovative non-destructive test method to evaluate the load carrying capacity of steel bolts anchored in concrete by co-relating their pull-out strength with Schmidt Hammer's rebound number. The variable factors such anchor bolt diameter, embedment length, its alignment, and concrete strength were also taken into consideration. The research team was also successful in combining the results of ultra-sonic pulse velocity test and Schmidt hammer test to improve the accuracy and reliability of estimated pull-out load carrying capacity. Saleem *et al.* 2017, provided the proof of concept of accessing the bond quality of steel reinforcement embedded in concrete by relating the ultra-sonic pulse velocity to the presence of crack in the vicinity of steel reinforcement. The researchers identified the delay in time for the ultra-sonic pulse to travel the fixed path length caused by initiation, development and propagation of internal cracks. The delay in pulse velocity to travel the fixed path length before and after the application of external loading was attributed to the presence of cracks in the concrete surrounding the steel bars. Direct and semi-direct method of investigation were used in UPV test and areas of bond degradation owing to crack initiation, development and propagation were identified. This led to the assessment of bond quality along the length of steel reinforcement. However, the fundamental weakness of the past research work was that only a single steel bar was used in the experimentation since its primary objective was to provide a proof of concept of using UPV test for bond evaluation. In the presented research work the authors take the past research work closer to reality by using a beam element having both tension and compression reinforcements along with shear stirrups. Fig. 1 depicts the conceptual diagram of the presented experimentation where a reinforced concrete beam is tested by applying gradually increasing loading in constant intervals and UPV readings are recorded at each stage. Through the delay in pulse velocity to travel the same path length, the initiation and development of internal cracking in ascertained. The percentage reduction in pulse velocity as a result of internal cracking resulting in deterioration of bond quality is reported as a comparison to unloaded condition which is referred to as neutral condition. This information allows engineers to identify locations of poor bond along the length of steel reinforcement thereby leading to localized strengthening resulting in saving of time, cost and labor.

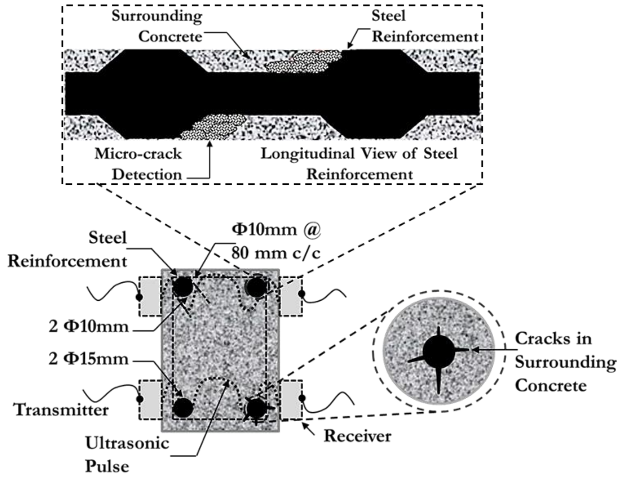

Fig. 1 Conceptual diagram detailing the investigation of internal micro-cracks along the length of steel reinforcement using UPV test

The presented innovation aims to add a new dimension to the ultra-sonic pulse velocity test method by allowing field engineers to judge and isolate areas of weak bond. The proposed method can be employed as a stand-alone tool and can also be used in conjunction with other NDTs for increasing the accuracy of on-site investigation. Furthermore, the confidence level and reliability of field engineer's judgement can also be improved by adopting the proposed technique.

2. Objectives

The fundamental objectives of the presented research work are provided as below:

To provide experimental evidence of using ultra-sonic pulse velocity to investigate the bond quality along the length of steel reinforcement embedded in concrete.

To provide experimental data which relates the reduction in ultra-sonic pulse velocity for the fixed path length of propagation with the development of internal cracks around the concrete surrounding the steel reinforcement as a result of increase in applied loading.

Highlight the various challenges that can be encountered by researchers/engineers when applying the proposed testing method in real-world situations along with shedding light on to the future direction of research and development.

3. Materials and methods

Four beam specimens 150x150x1000 mm were cast using Ordinary Portland Cement (OPC)-type 1 as shown in Fig. 2 along with six concrete cylinder specimens of 100 mm *Φ* and 200 mm height for testing the compressive strength of concrete. Steel reinforcement consisting of two 10 mm *Φ* bars at top and two 15 mm *Φ* bars at bottom were used as compression and tension reinforcement. Steel stirrups of 10 mm *Φ* with center-to-center spacing of 80 mm were used to arrest shear cracks from propagation. The beam element was designed to fail in flexure as that would allow for vertical cracks to develop greater than shear cracks. The rationale behind preferring the flexure failure as compared to shear failure was the reasoning that since the research team aimed to identify delay in ultra-sonic wave propagation with the initiation and development of internal cracks in the concrete surrounding the embedded steel reinforcement hence in this regards the flexure failure would assist the investigation. In the past research work aimed at developing proof of concept (see Saleem et al. 2017), the research team adopted two-point loading setup as it allowed for the creation of pure bending zone resulting in vertical cracks. However, a single point loading setup as shown in Fig. 3 was adopted as it allowed for a combination of flexure and shear cracking. Through experimentation the researchers were successfully able to detect the degradation on the bond quality owing to the initiation and development of internal micro-cracks.

All concreting was conducted using Ordinary Portland Cement (OPC) type-1 as it is the most commonly used cement in the construction industry. The air content of the mortar amounted to 6.1% by volume and initial and final setting time was recorded using a Vicat apparatus as 160 and 240 mins, respectively. The specific gravity of OPC was 3.19. Fine aggregate was substituted using desert sand which consisted of water absorption of 0.83% and specific gravity of 2.57 while limestone was used as coarse aggregate with maximum diameter of 18mm following the gradation curve as specified under ASTM C33. The bulk specific gravity and water absorption of limestone coarse aggregate was of 2.37 and 1.95%, respectively. The water-to-cement ratio of the concrete was set at 0.38 with fine to coarse aggregate ratio as 0.59 by mass. The slump reading of concrete was recorded as 100 mm and polycarboxylate ether was used as superplasticizer by 0.7% weight of cement.

Tension, compression and shear reinforcements were used in the reinforced concrete beams as shown in Fig. 2(b). The top and bottom cover for the reinforcement was provided as 50 mm and a 25 mm gap between the edge of steel reinforcement and concrete mold was provided in order to facilitate the placement of steel cage in the sample molds. The cover value was selected to allow ease of placement of transducers on the sides of specimens as shown in Fig. 3. Standard practice for casting and curing of concrete specimens as specified by ASTM C192 was adhered in order to achieve consistency and assure quality of specimens. Guide wires as shown in Fig. 2 and 4 were installed on the shear stirrup reinforcement to allow researchers to identify their locations. The reasoning behind this choice was that the research team wanted to identify the junction where the longitudinal steel reinforcement interacts with the shear reinforcement, this is important since the factors for adjustment of UPV wave velocity and corresponding transit time need to be adjusted for two conditions namely steel reinforcement perpendicular to the path of ultra-sonic wave travel (i.e. longitudinal steel reinforcement) and steel reinforcement parallel to the path of wave travel (i.e. shear reinforcement in between the two longitudinal steel). Whereas the reading locations in between these junctions could be adjusted by using a single factor for two steel reinforcements perpendicular to the wave propagation. These adjustment to wave velocities were applied to all the results in the presented manuscript. Furthermore, the locations marked A to D in Fig. 3 were used to take the UPV readings for the same transit length but without the presence of steel reinforcement. The reason behind this choice was to test the values of UPV readings for crack development through plain concrete. However, this testing is out of the scope of the current manuscript since it closely related to traditional testing of concrete using UPV test.

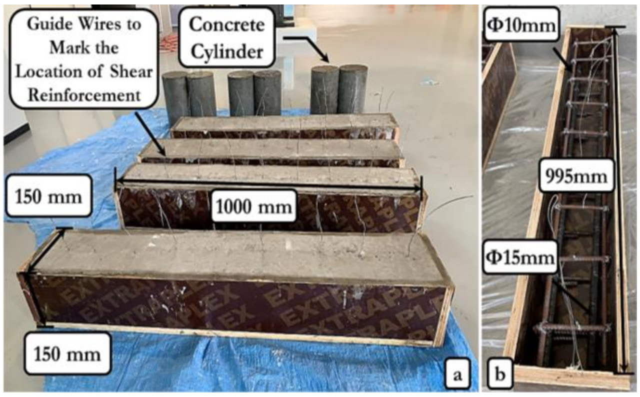

Fig. 2 (a) Test samples (a) Molds and Steel Reinforcement

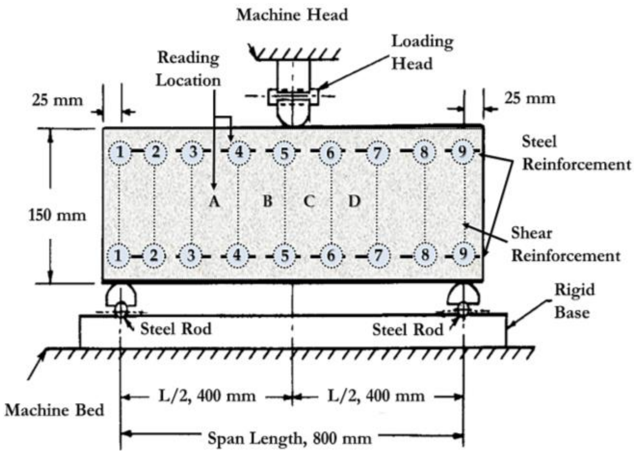

Fig. 3 Schematic illustration of test protocol

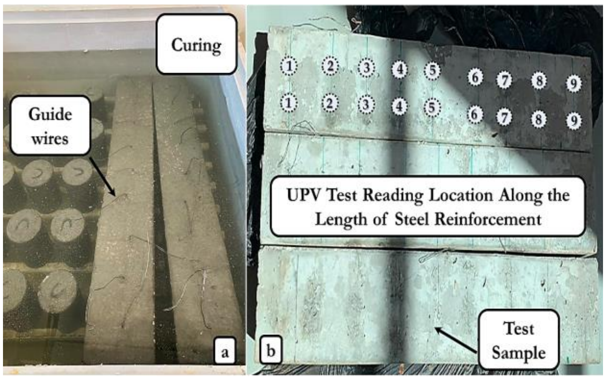

Fig. 4 (a) Curing of test specimens (b) UPV test locations along the length of steel reinforcement

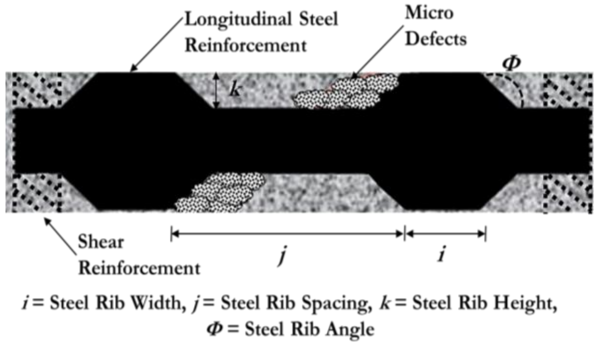

Fig. 6 Schematic illustration of factors affecting the bond performance of steel reinforcement

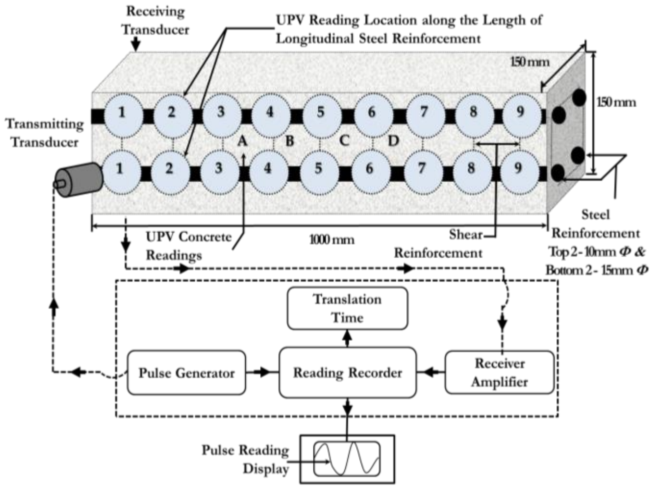

Fig. 5 Schematic illustration of UPV test protocol

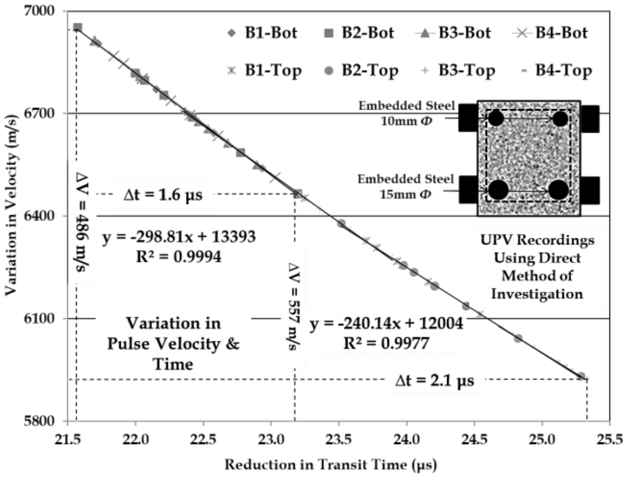

Fig. 7 Variation in pulse velocity and time before the application of loading under neutral condition for top and bottom zone

After casting, the samples were cured in the water tank as shown in Fig. 4 for 28 days and then placed outside the tank with wet jute bags covered with a plastic sheet in a temperature-controlled laboratory at 25°C ± 3°C. Cylinder specimens of 100 mm diameter with 200 mm height were tested as per ASTM C39 technical specifications to ensure quality and uniformity of test protocol. Six cylindrical specimens were tested by applying uniform axial loading on top till the samples reached failure. The average compressive strength was recorded as 30.95 MPa with a coefficient of variation of 1.6% which is within the acceptable limit of 3.2%. Fig. 5 depicts the UPV test setup. Nine reading were recorded along the length of embedded steel reinforcement as shown in the diagram, readings were recorded at the top and bottom of the beam element. UPV was recoded six times at each location. The readings were first located without the application of any external loading. This stage is referred to herein as the neutral condition. The values recorded in neutral condition served as benchmark for the remainder of tests. Through the analysis of the recorded reading the research team was successful in identifying weak spots in bond along the length of steel reinforcement.

Fig. 4(b) presents the applied test protocol of UPV readings marked along the length of the beam element. ASTM C597 standard was adhered to record UPV test readings using direct method of testing. Two beam elements were tested under flexure loading using ASTM C293-02 standard. The objective of this test was to estimate the peak load carrying capacity, P_{peak} of beam element. The peak load carrying capacity, P_{peak}, was used to the further testing on the remaining four beam samples. The samples were tested by gradually increasing the applied loading, the load was increased in equal increments of 10%. From the previously published research work (see Saleem *et al.* 2017), it was observed that the reduction in ultra-sonic pulse velocity begins to occur when load level reaches to approx. 10% of P_{peak}. From this point onwards the UPV continues to decrease with the increase in applied loading. This phenomenon can be attributed to crack development, bridging and propagation till the specimen reached P_{peak}. In view of keeping the interest of reader only the 25% increment of loading are reported in the manuscript. Since the general trends of the reduction in wave velocity are consistent throughout, hence the decision of reporting 25% increments has rationale basis. The average value of P_{peak} for the two specimens was recorded as 107.2 KN. In the presented manuscript the UPV test results are reported at 25% of P_{peak} at 26.8 KN, 50% of P_{peak} at 53.6 KN, 75% of P_{peak} at 80.4 KN and lastly at P_{peak}.

Fig. 5 and Fig. 4(b) illustrates the methodology adopted for recording the UPV test readings. The transducer and receiver were attached to the specimen surface after

Table 1 UPV readings before loading application using direct method of investigation in neutral condition – bottom zone

Read. Loc.	*T* (*μs*)	*V* (*m/s*)	*T* (*μs*)	*V* (*m/s*)	*T* (*μs*)	*V* (*m/s*)	*T* (*μs*)	*V* (*m/s*)
	Beam-1**		Beam-2**		Beam-3**		Beam-4**	
1	22.4	6707	22.2	6754	22.7	6614	22.1	6803
2	22.2	6750	22.1	6798	22.5	6656	21.9	6846
3	22.6	6644	22.4	6691	22.9	6551	22.3	6739
4	22.4	6707	22.2	6754	22.7	6614	22.1	6803
5	22.4	6707	22.2	6754	22.7	6614	22.1	6803
6	22.4	6696	23.2	6467	21.7	6912	23.0	6513
7	22.9	6541	22.8	6587	23.2	6466	22.6	6634
8	21.7	6904	21.6	6953	22.0	6808	22.4	6696
9	22.2	6771	22.0	6819	22.5	6677	21.8	6868

**The data provided in the table represents the fastest wave velocity corresponding to the lowest transit time (*μs*) recorded for the wave to travel fixed path length.

applying petroleum gel. Six readings were recorded at nine locations along the length of the beam element. The time for wave propagation through the width of the specimen was recorded in micro-seconds (*μs*). The wave velocity was calculated by dividing the path-length with the transit time (Tarun *et al.* 2004, Jones *et al.* 1969, ACI 2013). The frequency of transducer and wavelength was selected using BS 1881 (1986) and RILEM (1972) for an ordinary strength concrete with maximum aggregate size of 20mm to be 60kHz and 65 mm respectively. In the presented research work the researchers have presented the fastest wave velocity instead of average transit time with standard deviation. The rationale for this decision is based on the logic that since the UPV readings are significantly affected by human factor such as applied pressure on transducer and receiver and proper coupling. Hence the shortest transit time will occur only in the best test conditions thereby eradicating the human factor. This would lead to more consistent and reliable results. Hence, in order the eradicate human influence the rationale of choosing the fastest wave velocity has logical background.

4. Factors affecting ultra-sonic pulse velocity test

Fig. 6 illustrates the mechanical factors that affect the bond performance of steel reinforcement. In the presented research work much attention was paid to these factors as they have a significant effect on the bond performance of embedded steel reinforcement. These mechanical factors consist of *i* as rib width, *j* as rib spacing and *k* as rib height along with *Φ* as rib angle and *k/j* ratio. Furthermore, factors such as steel reinforcement diameter, its cover along with quality of concrete were also taken into consideration. In the current research work the researcher favored splitting type of failure as it allowed for longitudinal cracks along the length of steel reinforcement. Since, the fundamental objective of the presented work is to provide experimental evidence that the reduction in the ultra-sonic pulse velocity can be used to access the quality of bond of steel reinforcement by relating the reduction in ultra-sonic pulse velocity to the development of cracks in concrete surrounding the steel reinforcement, hence the splitting type of failure would assist in the experimental investigation. Furthermore, considerable attention was paid to the quality of concrete as it has a significant effect on the bond performance, efforts were made to produce concrete of uniform quality.

In order to eradicate human and errors and to standardize the testing protocol, ASTM C597 (2003) was followed for all testing. Factors such as concrete strength, age, maximum aggregate size, type of cement, moisture condition, curing, transit path length of the ultra-sonic wave, contact between transducer and receiver, transducer frequency and wavelength, presence of steel reinforcement perpendicular and parallel to the wave propagation path were all taken into consideration as per guidelines stipulated in BS 1881 (1986) and RILEM (1972). Proper coupling was ensured at each stage for recording readings and signal shape and strength of received waveform was monitored during testing and only sinusoidal waveform was recorded. Furthermore, all tests were conducted on reinforced concrete specimens at 38 days of casting in a temperature-controlled laboratory with temperature variation of 25 $\pm$ 3°C.

5. Results and discussion

The proceeding section details the experimental evidence that ultra-sonic pulse velocity test can be adopted to judge the quality of bond for steel reinforcement embedded into concrete. The research team has used the delay in ultra-sonic wave transit time for the fixed path length to identify the onset of internal cracking in the concrete surrounding the steel reinforcement. Hence, for this purpose the first step was to establish a set of reading that can serve as benchmark for the remaining testing. In this regards, Table 1 presents the set of reading for four beam samples prior to the application of loading. This condition is referred here onwards as the neutral condition and served as benchmark to compare reading after the applied loading. It is worth mentioning here that all the reported readings were taken using the direct method of

Table 2 UPV readings for bottom zone after the application of incremental loading measured via 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}**		0.50 P_{max}**		0.75 P_{max}**		P_{max}**	
1	28.0	5355	28.3	5295	29.2	5142	31.63	4742
2	28.0	5355	28.9	5185	30.4	4939	32.63	4597
3	28.5	5261	29.1	5149	29.5	5090	33.43	4487
4	29.0	5099	30.1	4978	31.1	4828	34.43	4357
5	30.3	4889	29.9	4988	34.1	4317	35.83	4186
6	29.4	5100	30.9	4850	31.9	4651	34.03	4408
7	28.6	5243	29.2	5132	30.3	4955	32.43	4625
8	29.0	5171	28.7	5221	29.3	5125	31.23	4803
9	27.4	5472	28.8	5203	30.3	4955	30.03	4995

** The presented depicts the reduction in pulse velocity (*m/s*) corresponding to the application of incremental loading measured via direct method of investigation.

testing, in the past research work by Saleem *et al.* 2017 the researchers were successfully able to adopt both direct and semi-direct method to provide proof of concept that UPV test can be used to judge the quality of bond, however, since in the presented experimentation the focus was to investigate the effect of two-way reinforcement, hence only direct method of testing was adopted. The in-direct method of UPV testing can be considered as topic for further research.

Fig. 7 presents the test results for UPV test on four beam specimens under neutral condition. The objective of this test was to investigate the quality of concrete, its uniformity and internal bond condition of the reinforced concrete beam specimens prior to the application of loading. The vertical axis of the result represents the wave velocity in *m/s* while the horizontal axis represents the wave transit time in μs. For the purpose of analysis, the beam element was sub-divided into two zones the top zone consisting of two 10mm Φ longitudinal steel reinforcement and 10mm Φ shear stirrup reinforcement and the bottom part consisting of two 15mm Φ longitudinal steel reinforcement and 10mm Φ shear stirrup reinforcement. The objective of using two different diameter reinforcements was to judges the variation in wave propagation velocity for the fixed path length. Fig. 7 depicts the results of wave transit velocity for the two zones prior to the application of loading. The presented result helps the research team judge the bond and concrete quality.

From the presented results it is evident that for bottom zone the wave transit velocity is slightly faster than the wave transit velocity through the top zone. The reason for this can be attributed to the presence of larger diameter steel reinforcement in the bottom zone, since the ultra-sonic wave transits faster through the steel reinforcement and a loss in wave signal strength occurs owing the interface of steel and concrete, hence the portion of wave that transits through the larger diameter steel reinforcement is larger in the bottom zone as compared to the top zone (see BS 1881 (1986), RILEM (1972) and Tauren *et. al.* (2004)). It can be seen from the result that the variation in the transit time for the top and bottom zone is 2.1 μs and 1.6 μs, respectively and the velocity for the wave propagation for all zones is above 5000 *m/s* which indicates a perfect bond condition and a good quality concrete. It is to be brought to the attention of the readers that in order to keep reader's interest only the bottom zone readings for pulse velocity and transit time under neutral condition are reported in Table 1. However, the proceeding section presents the detailed analysis of reduction in wave velocity with respect to increase in applied loading for both top and bottom zones.

The beam specimens were loaded under equal increments of 10% of P_{peak} till failure and reduction in wave velocity to travel the same path length was recorded using direct method of UPV testing. As illustrated in the conceptual diagram presented in Fig. 1 and Fig. 6, that as the applied loading increased the concrete surrounding the steel reinforcement starts to crack resulting in degradation of bond. It is worth noting that the degradation is bond was not uniform along the length of steel bar, some areas where the micro-cracks bridged and propagated showed a larger reduction in pulse velocity whereas other areas where micro-cracks were less prominent showed a lower percentage of pulse velocity degradation. Through this investigation the research team was able to access the bond quality along the length of steel reinforcement. In real-world situation this information would allow engineers to isolate critical areas for detailed investigation and this information can also be used for localized repairs thereby resulting in reduction of time, cost and labor needed for the maintenance of the infrastructure.

5.1 Bottom zone evaluation

As mentioned earlier the beam specimens was sub-divided into top and bottom zones based on the variation in longitudinal steel diameter. The results presented in this section detail the experimental investigation for the bottom zone which contained two 15mm Φ longitudinal steel reinforcement and 10 mm Φ shear stirrup reinforcement. Nine locations were marked along the length to RC beam specimen as shown in Fig. 3, 4 and 5 with transmitting and receiving transducers positioned on either side of the

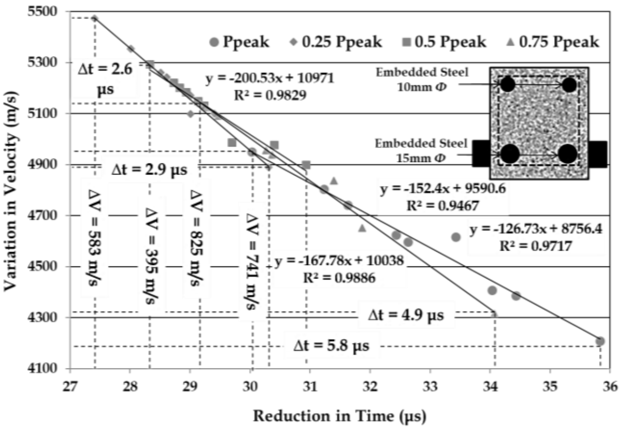

Fig. 8 Variation in wave velocity with incremental loading (direct method – bottom zone)

Table 3 Percentage reduction in pulse speed with regards to neutral condition (bottom zone - direct method)

Loading Range (%)	Range of Pulse Velocity (*m/s*)		Reduction in Velo. (*m/s*)	% Reduction w.r.t Neutral (*%*)	% Reduction w.r.t P_{peak} (*%*)
Neutral	6953	6467	486	-	34.91
0~25	5472	4889	583	24.40	13.91
25~50	5295	4900	395	24.23	14.10
50~75	5142	4317	825	33.24	2.50
P_{peak}	4950	4209	741	34.91	-

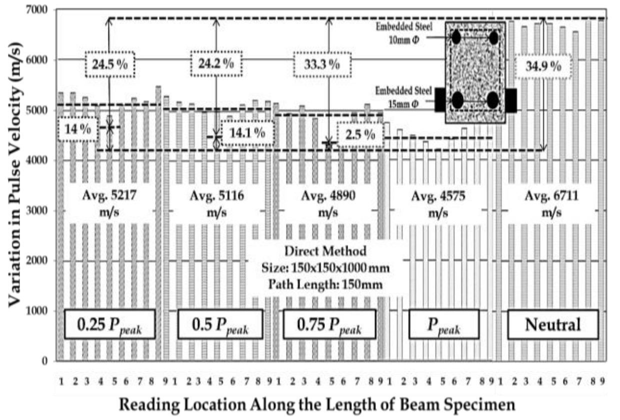

Fig. 9 Reduction in pulse velocity along the length of steel reinforcement embedded in concrete with increase in applied loading in comparison to neutral condition for bottom zone

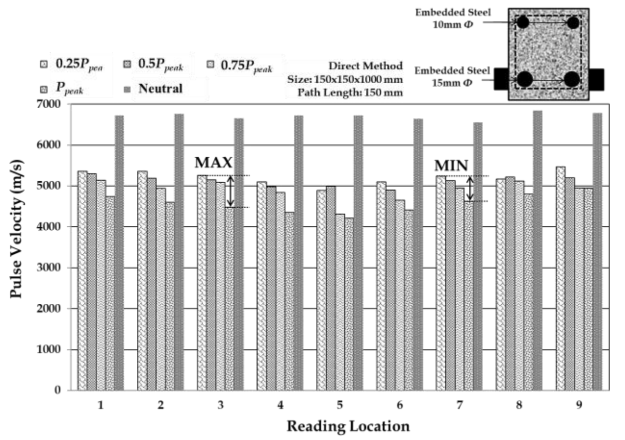

Fig. 10 Variation in pulse velocity along the length of steel reinforcement embedded in concrete for bottom zone with the application of incremental loading

specimen and the fastest pulse velocity corresponding to the shortest transit time was recorded. It is known that the ultrasonic pulse travels 1.4 to 1.7 times faster in steel as compared to concrete hence correction factors for two types of steel reinforcements present in the transit path of the pulse velocity were calculated using the iterative process as suggested by BS 1881. These correction factors were chosen as 0.965 for L_s/L ratio of 1/5 for steel reinforcement perpendicular to the path of transit and 0.92 for L_s/L ratio of 1/10 for steel reinforcement parallel to the path of wave transit corresponding to very good quality concrete with V_c of 5000 m/s. All testing was conducted on air dried samples in a temperature-controlled laboratory and only the stable pulse velocity readings corresponding to sinusoidal wave were recorded. Table 2 presents the recorded reading of the nine locations.

Fig. 8 illustrates the decrease in the pulse velocity with the increase in the applied loading. It can be seen from the result that as the applied loading increases the pulse velocity starts to decrease. This can be attributed to the degradation in bond quality of steel reinforcement as the concrete surrounding the steel refinement starts to cracks. From the presented result it can be seen that although there is a consistent decrease in the pulse velocity however for loadings of 25% of P_{peak} and 50% of P_{peak} the range is almost consist. This phenomenon can be linked to the fact that initially once the cracks start to develop these cracks do not have enough length to bridge together and start propagating, however as the loading is increased to 75% of P_{peak} these cracks start bridging together with other cracks in the vicinity which resulted in larger drop in the pulse velocity. The results hold consistency with previous findings of past researchers (see Saleem *et. al.* 2017, 2018). Table 3 presents the percentage decrease in the pulse velocity with respect to increase in applied loading. The pulse velocity decreased by approximately 25% for 25% of P_{peak} and 50% of P_{peak} while a larger drop of 33% and 35% in pulse velocity occurred after the application of 75% of P_{peak} and P_{peak}. This confirmed the presented hypothesis that in the ranges of 25% of P_{peak} and 50% of P_{peak} the concrete in the vicinity of steel reinforcement starts to develop cracks, however these cracks are small in length and are not bridged with other adjacent cracks. As the loading is increased to 75% of P_{peak} and P_{peak}. These cracks bridge together with adjacent cracks and start to propagate resulting in a significant drop in velocity. Fig. 9 presents the reduction in pulse velocity with the increase in the applied loading. Fig. 10 presents the variation in pulse velocity along the length of steel reinforcement, nine locations marked along the length of the reinforcement indicate the bond condition for each incremental loading. It can be seen that at each stage the velocity continues to decrease with the increase in loading. This result allowed the research team to

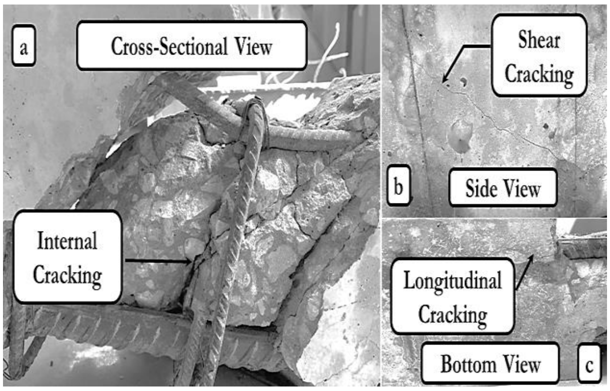

Fig. 11 Experimental evidence of internal cracking in the concrete surrounding the steel reinforcement (a) Cross-sectional view (b) Side view (c) Bottom view

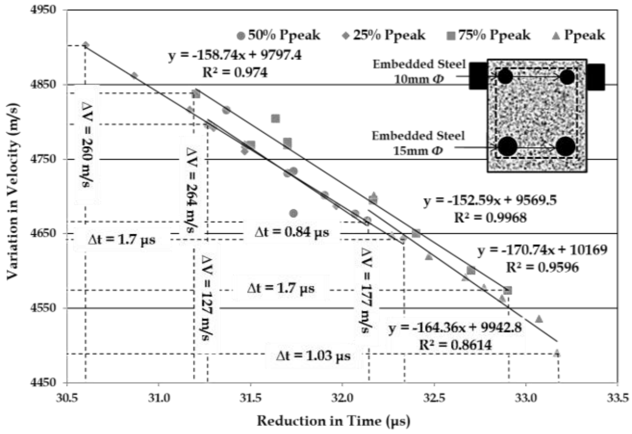

Fig. 12 Variation in wave velocity with incremental loading – top zone

identify areas of bond degradation along the length of embedded steel. It can be seen that the location 3 has the highest drop in pulse velocity owing to crack development in the concrete surrounding the steel reinforcement while location 7 resulted in the minimum bond degradation depicting lower cracking. Fig. 11 presents the cracking pattern for the reinforced concrete beam specimen. The results presented in Fig. 8, 9, 10 and 11 provide information that can be used to isolate areas of further investigation and can also indicates key areas that can be strengthened locally thereby lowering the time, cost and effort needed for infrastructure maintenance. From the presented results it can be seen that as the cracks develop, bridge together and propagate the pulse velocity decreases. The proceeding section details the experimental investigation results for the top zone of the RC beam specimen.

5.2 Top zone evaluation

Similar to the bottom zone nine locations were marked along the length of RC beam specimen as shown in Fig. 3, 4 and 5 in the top zone. The top zone of RC beam specimen consisted of two 10 mm *Φ* longitudinal steel reinforcement along with 10 mm *Φ* shear stirrup reinforcement placed at 80 mm c/c spacing. The objective of dividing the beam into top and bottom zones was to allow the research team to test the presented method for two types of steel reinforcement. The factor of 0.985 was chosen using the methodology as presented in the previous section (see BS 1881 and RILEM 1972). Fig. 7 illustrates the variation in pulse velocity readings prior to the application of loading. From the presented result it is evident that average pulse velocity is above the 5000 *m/s* indicating a good quality concrete, furthermore, the variation in transit time along the length of the RC beam specimen is 2.1 *μs* which indicates a perfect bond condition.

Table 4 presents the variation in pulse velocity readings after the application of loading. Fig. 12 depicts the reduction in pulse velocity reading after the application of loading increment. It can be seen from the presented result that as the applied loading increases the pulse velocity starts to reduce. However, after the initial drop in pulse velocity values there is gradual reduction in velocity. The presence of cracks coupled with the increase in pulse velocity transit time for the same path length indicates the degradation in bond quality of the embedded steel reinforcement. However, it was noticed during experimentation that the reduction in pulse velocity for the top zone is lower as compared to the bottom zone. The explanation for this phenomenon can be attributed to the fact that the top zone experienced less cracking as compared to the bottom zone. The bottom zone of the RC member experienced both shear and flexure cracking as shown in Fig. 11 while the top zone experienced predominantly flexure cracking with shear cracks only developing near the P_{peak} as shown in Fig. 15.

Table 5 presents the percentage reduction in pulse velocity with respect to the applied loading. After the initiation of internal cracking there was sudden drop in pulse velocity indicated by the increased transit time for the same path length, this can be attributed to the crack propagation followed by crack bridging. Fig. 13 presents the variation in the pulse velocity after the application of loading. From the presented result it can be seen that there is approximately 22% decrease in pulse velocity for 25% of P_{peak} followed by 22% and 23% reduction for 50% and 75% of P_{peak} loading application while the largest drop occurs after the application of P_{peak} at 24.5%. Fig. 14 represents the variation in pulse velocity along the length of steel reinforcement. Using the presented result, it is possible to identify locations of weak bond along the length of steel reinforcement. It can be seen from the figure that the maximum drop in pulse velocity occurs at location 9 along the RC beam element. The reduction in pulse velocity coupled with the presence of crack bridging as shown in Fig. 15 indicate the degradation in bond. The figure depicting the full beam length see Saleem *et. al.* 2017. From the analysis of the presented results it is evident that the proposed technique can be used to identify the locations of weak bond along the length of steel reinforcement embedded in concrete. Furthermore, the combined use of the presented methodology can lead to increase the confidence level of field-engineers thereby leading to reduction in time, cost and efforts needed for repairs and rehabilitation of infrastructure.

Table 4 UPV readings for top zone after the application of incremental loading measured via 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}**		0.50 P_{max}**		0.75 P_{max}**		P_{max}**	
1	31.5	4766	31.7	4732	31.6	4805	32.2	4701
2	31.3	4792	31.4	4816	31.7	4773	32.9	4563
3	32.0	4687	31.9	4702	32.2	4695	32.8	4577
4	31.5	4770	31.3	4797	32.4	4651	32.1	4667
5	31.5	4760	32.1	4677	31.2	4838	33.1	4536
6	30.6	4903	32.1	4668	31.7	4769	32.5	4620
7	32.3	4643	31.7	4734	31.5	4769	32.3	4648
8	30.9	4862	31.7	4678	32.9	4574	32.7	4591
9	31.2	4816	32.1	4668	32.7	4601	33.2	4490

** The presented depicts the reduction in pulse velocity (*m/s*) corresponding to the application of incremental loading measured via direct method of investigation.

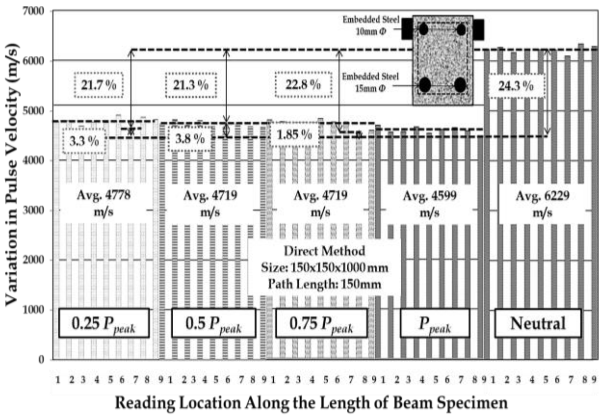

Fig. 13 Reduction in pulse velocity along the length of steel reinforcement embedded in concrete with increase in applied loading in comparison to neutral condition for top zone

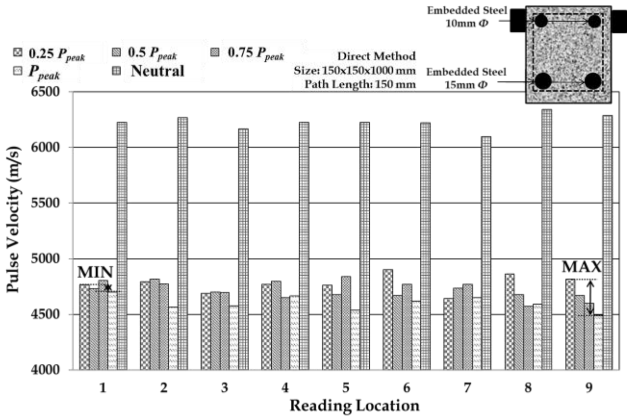

Fig. 14 Variation in pulse velocity along the length of steel reinforcement embedded in concrete for top zone with the application of incremental loading

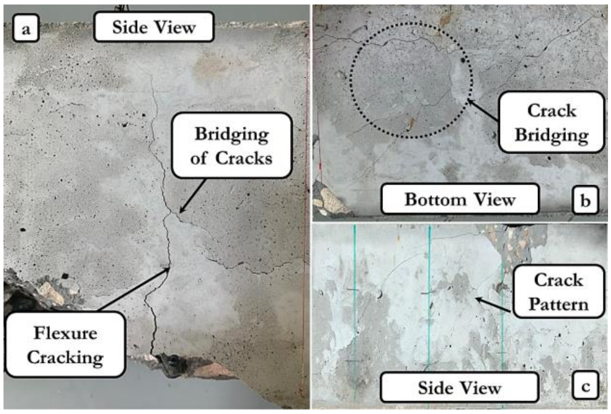

Fig. 15 Experimental evidence of cracking (a) Cross-sectional view (b) bottom view (c) side view

6. Real-world application challenges and strategy

The proceeding section details the real-world challenges and implementation strategy that can be adopted by fellow researchers and engineers to take advantage of the presented innovative technique of using UPV test to access the quality of bond in reinforced concrete members. The idea is to convey to the readers the challenges and planning needed for applying the presented research technique to access the structural condition.

The first and foremost task for the structural assessment team is to study the available structural drawings to develop and idea about the design of the structure. Since the method is intended to be implemented via trained engineers and laboratory technicians hence, during the preliminary site-visit the team should take into account factors such as type and age of concrete, its moisture condition, environmental condition etc. After selecting the primary spot for investigation, the team should mark a grid pattern on the area of interest. The size and spacing of the grid will be governed by the size of the structural element. Readings should be recorded at each location and only the fastest stable reading should be considered for analysis. From the analysis of the recorded readings the bond condition of the steel reinforcement can be accessed. It is to be stressed here that the authors recommend the researchers to combine the proposed method along with other traditional non-destructive testing methods to increase the reliability and efficiency of field investigation and by combining the data analysis the accuracy of the judgement of field engineer can also be increased.

For sites where the structural drawings are not available or in case of structural assessment of old historical/heritage buildings, where engineers are not allowed to conduct destructive testing and the site requires strengthening. In such cases, the researchers believe that the best option would be to start preliminary investigation after shortlisting the areas of interest by using re-bar scanner and combining the proposed method with other NDTs for gathering of large quantities of data. The application of such methodology will yield most fruitful results leading to requiring the shortest amount of time and labor needed for the job.

Furthermore, the research team envision that the proposed method can be particularly useful for remote-sensing option where areas that are of great interest to the engineers can be continuously monitored using the proposed technique for large scale structures such as dams, bridges etc. This would allow engineers to have a real-time feedback with regards to degradation in bond quality of steel reinforcement after any major event such as earthquake, snowstorm, wind loading etc. In this regard by applying the above-mentioned strategy the proposed method can be effectively and efficiently adopted for application in real-world structural evaluation.

7. Conclusions

An experimental investigation regarding the bond performance evaluation of reinforced concrete beam has been presented. The objective of the investigation was to provide experimental evidence relating the reduction in pulse velocity to the development of cracks in the concrete surrounding the steel reinforcement. Experimental evidence related to two diameters of steel reinforcement along with shear reinforcement is presented. From the analysis of the presented results the following conclusions can be drawn:

- Using UPV testing method, areas of bond degradation along the length of steel reinforcement embedded in concrete beam can be successfully identified.
- The ultra-sonic pulse velocity decreases with bond degradation. By adopting direct method for investigation for tension zone (bottom zone) 24.4%, 24.3%, 33.4% and 35% reduction in pulse velocity was recorded in comparison to neutral unloaded condition for increase in loading to 25% of P_{peak}, 50% of P_{peak}, 75% of P_{peak} and P_{peak} respectively.
- Also for compression zone (top zone) 22%, 21.5%, 23% and 25% reduction in pulse velocity was recorded in comparison to neutral unloaded condition for increase in loading to 25% of P_{peak}, 50% of P_{peak}, 75% of P_{peak} and P_{peak} respectively. The lower reduction in UPV can be attributed to reduced cracking in the compression zone.

The presented innovative research work has possibility of adding a new dimension to the ultra-sonic pulse velocity test. Furthermore, combining the presented methodology with other non-destructive tests can result in increased reliability and accuracy of field investigation.

8. Range of application

The presented research work details the use of ultra-sonic pulse velocity test method for investigating the quality of bond in reinforced concrete beams. This presented method has the potential to add a new dimension to UPV test method. This kind of evaluation can allow field-engineers to quickly isolate areas for detailed investigation. The combined use of the presented method with other non-destructive testing techniques can allow for increased reliability and accuracy of judgement of on-site engineering tests. This can lead to localized repairs/strengthening of effected areas thereby resulting in reducing of time, cost and effort needed for infrastructure maintenance. However, it is to be brought to the notice of the readers that for any test method to be universally acceptable, it needs are vast data bank of reliable experimental results. In this regards the presented experimental evidence provides validity to the claim that UPV test method can be used for identifying weak spots along the length of steel reinforcement embedded in concrete. The presented experimental evidence is valid for reinforced concrete beam of 150 x 150 x 1000 mm having two tension and compression steel reinforcement of 15 mm diameter and 10 mm diameter with shear stirrups of 10 mm diameter having 80 mm c/c spacing. Further experimentation is needed for other steel bar diameters. Furthermore, the cut-off value of maximum beam width that can be reliably tested using the UPV test method is another avenue of future research and development.

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