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Evaluating the pull-out load capacity of steel bolt using Schmidt hammer and ultrasonic pulse velocity test

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Abstract. Steel bolts are used in the construction industry for a large variety of applications that range from fixing permanent installations to temporary fixtures. In the past much research has been focused on developing destructive testing techniques to estimate their pull-out load carrying capacity with very little attention to develop non-destructive techniques. In this regards the presented research work details the combined use of ultrasonic pulse velocity and Schmidt hammer tests to identify anchor bolts with faculty installation and to estimate their pull-out strength by relating it to the Schmidt hammer rebound value. From experimentation, it was observed that the load capacity of bolt depends on its embedment length, diameter, bond quality/concrete strength and alignment. Ultrasonic pulse velocity test is used to judge the quality of bond of embedded anchor bolt by relating the increase in ultrasonic pulse transit time to the presence of internal pours and cracks in the vicinity of steel bolt and the surrounding concrete. This information combined with the Schmidt hammer rebound number, R, can be used to accurately identify defective bolts which resulted in lower pull-out strength. 12 mm diameter bolts with embedment length of 70 mm and 50 mm were investigated using constant strength concrete. Pull-out load capacity versus the Schmidt hammer rebound number for each embedment length is presented.

Keywords: steel bolt; embedment length; bond quality; non-destructive testing; load carrying capacity; impact loading; rebound number; ultrasonic pulse velocity test

1. Introduction

Non-destructive testing (NDT) technology has revolutionized the construction industry. NDT is used extensively in the construction industry to evaluate the condition of existing structures and provides engineers with a tool to estimate the strength of materials and components without destroying or modifying them. In this regards Saleem *et al.* 2016 presented a new non-destructive testing procedure to evaluate the pull-out load carrying capacity of concrete anchor bolts by relating their pull-out strength to the Schmidt hammer rebound number. The researchers were successfully able to identify defects related to anchor bolt installation and were able to accurately estimate the reduction in pull-out strength owing to the defects using the proposed non-destructive testing procedure. During experimentation it was observed that the bond strength of the bolt was influenced by its diameter, its embedment length, alignment and the concrete strength. However, in the past research work the embedment depth and concrete strength was kept constant and only the variation in the bolt diameter was investigated. The presented manuscript is an advancement in terms of improvement in reliability and accuracy as it combines the use of two non-destructive testing techniques instead of one, to provide reliable data that can be used to accurately identify anchor bolts with faulty installation. This new innovation along with studying the effect of varying the embedment length on the pull-out load carrying capacity has led the researcher to develop the presented new method that can be reliability used to judge the pull-out strength of concrete anchor bolts using non-destructive evaluation.

In-addition, the presented manuscript also details the use of ultra-sonic pulse velocity (UPV) test to judge the bond quality of concrete anchor bolt by relating the pulse velocity to the presence of internal cracking. Saleem *et al.* (2017) recently developed a new application of ultra-sonic pulse velocity test by relating the variation in pulse velocity to the bond quality of reinforced concrete beams. The benefit of combining the use of Schmidt hammer and ultra-sonic pulse velocity test is to give researchers/practicing engineers the ability to accurately identify bolts with improper installation, which result is lower pull-out strength. By using the presented non-destructive testing strategy the research team was successfully able to pin-point bolts with improper installation which resulted in low pull-out strength. This breakthrough also adds a new dimension to the previously proposed findings. By taking into account the information provided by UPV test about the bond condition of the embedded anchor bolt along with the rebound number the researchers can effectively identity defects in the installation of anchor bolt. Thereby resulting in increased efficiency and accuracy of the testing procedure. Eligehausen *et al.* (2008a), (2008b), Guillet *et al.* (2011), Jie *et al.* (2007), Philipp *et al.* (2016), Saleem *et al.* (2016), (2014), (2010) researched the response of

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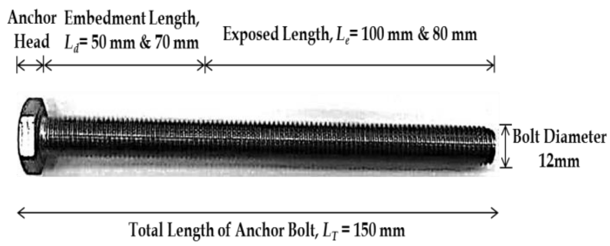

Fig. 1 Sample anchor bolt

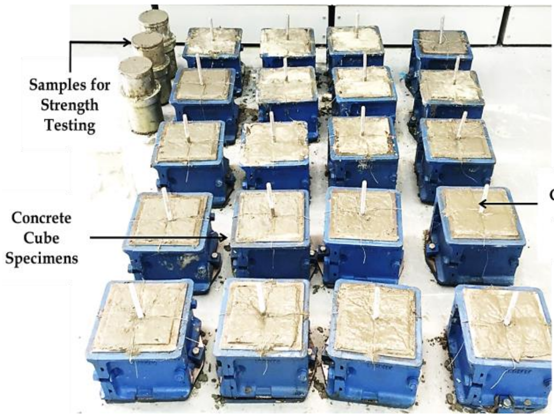

Fig. 2 Concrete samples for testing

concrete anchors subjected to various types of loading under stressed and non-stressed conditions. They also investigated the deformational behavior of the anchor bolts and their design details to refine the dynamic response of anchor bolts. However, all of the research work is focused on the destructive evaluation of the anchor bolts without any emphasis on the non-destructive evaluation. Torabi *et al.* (2010), Cargill and Shakoor *et al.* (1990) realized the potential use of impact energy imparted by the Schmidt hammer and utilized it to the correlate the strength of rock specimens. They also produced quantitative analysis results. Similarly, Jen *et al.* (2009), Katalin *et al.* (2013), Brozovsky and Zach *et al.* (2011) provided experimental evidence related to the angle of impact, surface properties of concrete and their effect on the rebound number. They also took into consideration the design parameters of concrete. Mutlib *et al.* (2016), Mandel *et al.* (2016) and Umais *et al.* (2017) used ultrasonic pulse velocity test to investigate the performance of buildings and bridges. They also investigated the effect of rapid-hardening cement, aggregate type, its size, influence of age of concrete, its workability and found that UPV test is a useful tool to investigate the properties of concrete in a non-destructive manner. Similarly, Qasrawi *et al.* (2013) and Zongping *et al.* (2014) investigated the effects of additives such as GGBFS, chloride intrusions on the response of ultrasonic pulse velocity. Saleem *et al.* (2017), (2010) used ultrasonic pulse velocity test to investigate the bond of concrete elements and found that ultrasonic pulse velocity can be related to the presence of internal cracking at the interface of concrete and embedded steel.

Keeping in mind the past mentioned research the main objective of the presented research work is to combine the UPV test with the Schmidt hammer rebound value to give

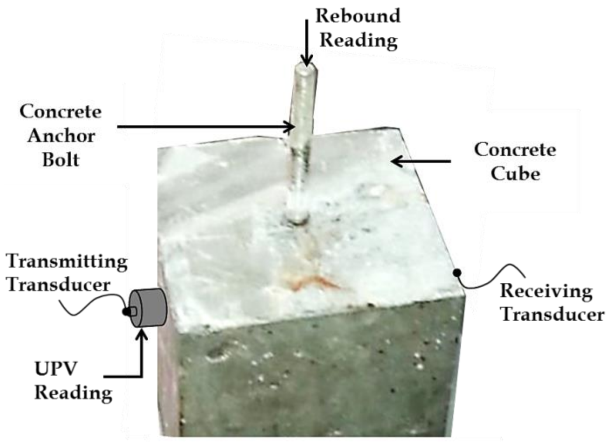

Fig. 3 Cube specimen depicting the Schmidt hammer and UPV testing

engineers/researchers the ability to accurately identify faulty steel bolts using non-destructive testing. Furthermore, the results provided in the manuscript give additional validity to claim of relating the Schmidt hammer rebound number to the steel bolt pull-out strength for varying embedment length. Various factors effecting the pull-out load carrying capacity such as bolt alignment, presence of internal cracking, air voids, water pockets are also distinguished by combining the results provided by Schmidt hammer rebound number and ultrasonic pulse velocity. 12 mm Φ steel bolts as shown in Fig. 1 having an embedment length of 50 mm and 70 mm, embedded in normal strength concrete are investigated in the presented manuscript.

2. Methodology

Forty 150×150×150 mm cube specimens and six 150×300 cylindrical specimens for compressive strength testing were casted as shown in Fig. 2, using ordinary Portland cement (Type-I) with a specific gravity of 3.15 in accordance with 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%. The water-cement ratio of 0.41 with water content was 120; cement 290 kg/m^3, air entrainment 4.2%; sand and gravel 828 and 1043 kg/m^3, respectively. Limestone course aggregate with a maximum size of 19 mm was used and it was graded in accordance with ASTM C33, having a bulk specific gravity and water absorption of 2.45 and 2.05%, respectively. The slump was 100 $\pm$ 25 mm, curing was done in the temperature-controlled water tank and the average 28 days compressive strength was 34.1 MPa. Pre-construction installed steel anchor bolt with varying embedment length were studied in the presented research work as shown in the Fig. 1. The total length, L_T, of the anchor bolt was 150 mm. Embedment length, L_d, of 50 mm and 70 mm along with exposed length, L_e, 100 mm and 80 mm respectively. Anchor bolt was centered in the

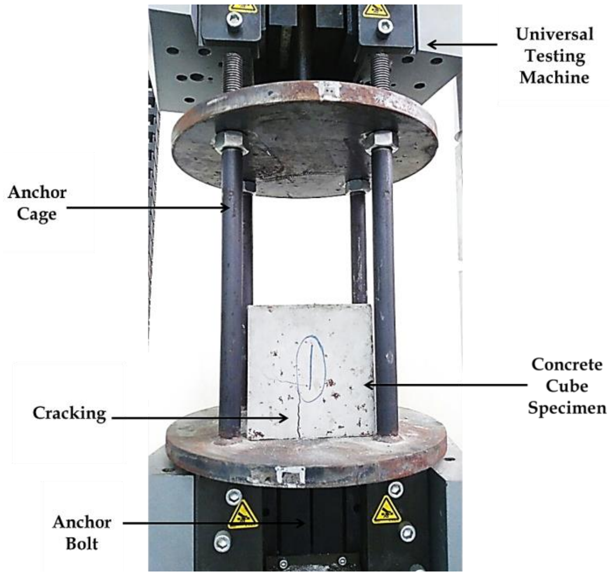

Fig. 4 Pull-out testing setup

middle of the cube mold with the help of guide wires. The embedment depth was also maintained using the guide wire mechanism. Fig. 3 shows the prepared sample after curing. Five rebound readings of Schmidt hammer were recorded on bottom the anchor bolt, average value of these readings were used for analysis. During the reading recording procedure, care was taken to vertically align the bottom of anchor bolt to the tip of Schmidt hammer, the verticality was ensured through visual inspection. Through past experiment, Saleem *et al.* 2016, noticed that the verticality of the anchor bolt plays a crucial role in its load carrying capacity. Anchor bolts with ill-alignment greater than 15^o were not suitable for rebound testing as the tip of the rebound hammer would slip owing to large ill-alignment. However, in the presented experimental evidence much care was exercised to avoid this error and the reported reading are free from large ill-alignment effects. The reported ill-alignment was measured using image analysis technique where the image of ill-aligned anchor bolt was superimposed on the straight anchor bolt and the ill-alignment was recorded in degrees

Fig. 4 presents the pull-out test setup. The author invested a new anchor cage (US Patent Pending) as shown in the Fig. 4 that can be employed to conduct pull-out strength testing with the help of universal testing machine (UTM). The cube specimens were inserted in the anchor cage and whole assembly was fixed in the UTM. This test setup is not only economical as it eradicates the need of a separate pull-out testing device but it also has the added benefit that the pull-out load versus displacement plots can be obtained from the UTM directly further eradicating the need of complex data recording setup, LVDTs and measuring gauges. Thereby, leading to a simple, efficient Fig. 5 presents the flow chart of research methodology. Initially trial batches were casted to finalize the mix design, afterwards anchor bolts were installed inempty concrete cubes prior to concrete casting. The embedment depth and the bolt alignment was adjusted using guide wires. After curing the samples were demolded and guide wires were

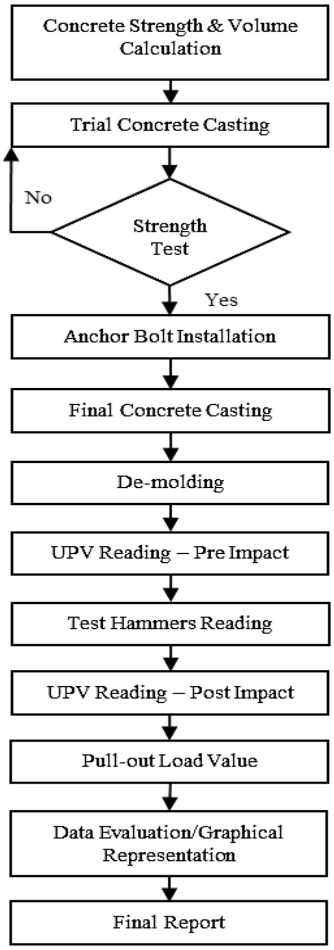

Fig. 5 Flow chart of research methodology and effective test setup

removed in order to avoid any interference with the ultrasonic pulse velocity testing. UPV readings were recorded in accordance with ASTM C597 (2003). The sample dimension, aggregate size, size of anchor bolt, frequency, concrete moisture condition, temperature and the presence of anchor bolt perpendicular to the pulse propagation path were all taken into consideration in accordance with BS 1881 (1986); RILEM (1972) and Tarun *et al.* 2009. Furthermore, the transducer and receiver were firmly placed on the opposite ends of the cube as shown in Fig. 3; and petroleum jelly was used to ensure proper coupling between the transducer and the cube specimen. The wave velocity was calculated by dividing the fastest time in microsecond (μs), taken by the ultrasonic wave to travel through the 150 mm width of the specimen. 54 kHz frequency with the wavelength of 68 mm in was chosen for the normal strength concrete with the maximum aggregate size of 19 mm, in accordance with BS 1881 (1986) and RILEM (1972). Prior to testing it was ensured that the UPV testing equipment is calibrated and their exist no air pocket between the transducer and the concrete cube. Three reading locations were chosen along the embedment depth of anchor bolt. Furthermore, three readings were recorded at each location. The shortest transit time corresponding to the fastest wave travel time is reported in the presented manuscript. The reason behind reporting the fastest wave

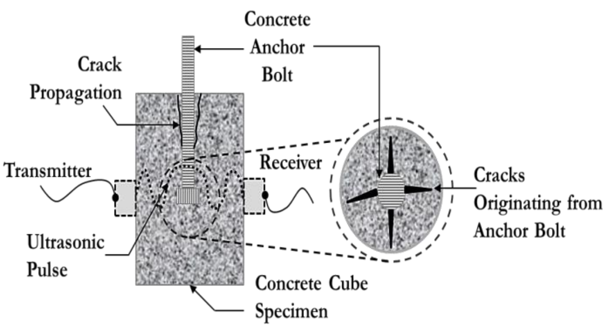

Fig. 6 Conceptual diagram of crack propagation around the embedded anchor bolt

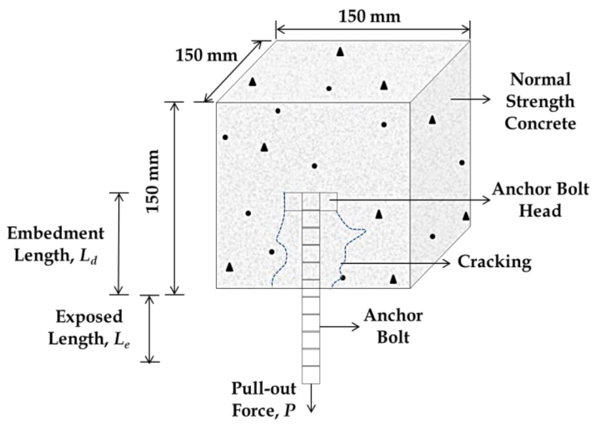

Fig. 7 Schematic diagram showing anchor bolt installation and cracking pattern

Fig. 8 Crack along the anchor bolt embedment length

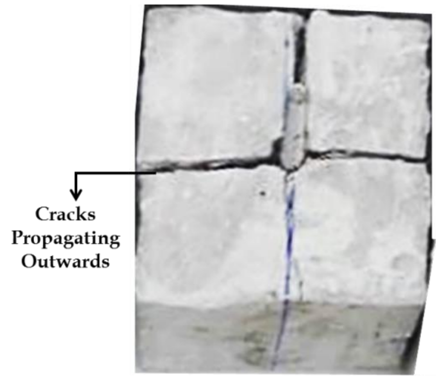

Fig. 9 Cracking on top of the anchor bolt

travel time is based on the rational that since the wave velocity is affected by proper coupling which is ensured by pressure exerted by the operator. Hence, the fastest travel time would correspond to the reading which resulted owing to perfect coupling, thereby minimizing human error and increasing the reliability of the presented readings. All the factors affecting the bond performance of the embedded anchor bolt were taken into consideration and much effort was exercised in producing a consistent quality of concrete in order to ensure uniformity in the bond quality along the embedment length of anchor bolt. Correction factor of 0.98 related to the presence of 12 mm Φ diameter anchor bolt present perpendicular to the propagation path of ultrasonic pulse was applied to all the reported readings in the presented manuscript. Furthermore, all the UPV testing was conducted on air dried samples after 28 days of curing and attention was paid to the strength and shape of the received waveform and only sinusoidal shape waveforms were recorded.

3. Factors affecting bond and pull-out strength

Casting of the concrete samples was conducted in three layers of equal thickness and tampering rod was used to compact the concrete. 25 evenly distributed blows were imparted in each layer and the concrete surface was leveled using a trowel. Since the bond quality of anchor bolt plays a crucial role on its overall load carrying capacity, much care was exercised in compacting the concrete layers. It was noticed during experimentation that concrete samples with poor quality concrete displayed longer transit time for ultrasonic pulse to travel through the concrete cube. A set of five readings were recorded on the top of each anchor bolt as shown in Fig. 3. The energy imparted by the Schmidt hammer is transferred to the concrete surrounding the anchor bolt. The bolt which had a strong bond was successfully able to transfer the impact energy to the surrounding concrete, resulting in a higher rebound number. Whereas the bolt with porous bond was unable to transfer the impact energy and resulted in cracking in the concrete surrounding the steel anchor bolt, this lead to a lower rebound number. The presence of internal cracking was successfully detected through the use of ultrasonic pulse velocity test. Fig. 6 shows the conceptual schematic diagram depicting the internal cracking at the concrete steel interface. The velocity of ultrasonic wave is faster in the perfect bond specimens while the specimens with lower bond quality resulted in slower transit time for the same path length. The combination of rebound number with UPV test allowed the researchers to successfully identify anchor bolts with poor bond thereby resulting in lower pull-out load carrying capacity.

Fig. 7 depicts the conceptual diagram of internal stress distribution along with the cracking pattern. Traditional pull-out tests lead to a cone type of failure however, owing to the reaction provided by the test setup, as shown in Fig. 4, anchor bolt experienced radial stress distribution resulting in circumferential crack propagation. A similar cracking pattern was observed during experimentation as shown in Figs. 8 and 9 depicting a strong co-relation between the conceptual theory and practical experimentation. The bond between the steel bolt and the surrounding concrete can be categorized into two main classes. Namely, mechanical bond resulting from the interlocking between the bolt grooves and the surrounding concrete. The second category of the bond is referred as the frictional bond that occurs between the bolt and the cracked concrete surrounding the bolt. Upon initial loading, the mechanical bond is dominant and is responsible for the load carrying capacity, however, as the loading increases beyond the fracture strength, the micro-cracks develop at the steel concrete interface. Upon further increase in loading these cracks bridge together to form large propagating vertical cracks as shown in Fig. 8, where the frictional bond is dominant. This process continues till the vertical cracks traverse the entire embedment length of the steel bolt. At this point in the loading all the mechanical bond along the length embedment length of the steel bolt has shifted from mechanical to frictional bond and afterwards the pull-out process is initiated, where upon further increase in loading the bolt is pulled out of the embedded concrete. At this stage the radial cracks appear as shown in Fig. 9. The reason behind the delay in occurrence of radial cracking is the fact that the vertical cracks move from bottom of the anchor bolt towards the top. Finally, these vertical cracks result in the crushing of concrete leading to the eventual pull-out of the embedded anchor bolt as shown in Fig. 8 and 9.

4. Results and discussion

Table 1 presents the values of Schmidt hammer rebound number corresponding to the pull-out load strength. Table 2 presents the time taken by the ultrasonic pulse to travel 150 mm width of the cube specimen. The presented reading has been adjusted for correction factor related to a single steel bar embedded perpendicular to the path of wave propagation in a good quality concrete with the maximum aggregate size of 19 mm. This correction factor was applied in accordance with BS 1881 and RILEM 1972 owing to the variation in ultrasonic pulse propagation speed though concrete and steel. Through the combined analysis of data presented in Tables 1 and 2, the researchers are able to identify the anchor bolts with poor quality of bond. As mentioned in the previous section the anchor bolts with good quality of bond depict a higher rebound number as they are successfully able to transfer the impact energy to the surrounding concrete. Furthermore, these anchor bolts depict a lower pulse velocity transit time resulting in a faster ultrasonic pulse velocity. On the contrary the anchor bolts with porous bond depict lower rebound number with larger variation among individual rebound readings and longer transit time resulting in a slower ultrasonic pulse transit velocity.

Fig. 10 presents the variation in ultrasonic pulse velocity along the depth of the 12 mm Φ diameter anchor bolt with 50 mm embedment length. The data presented in the figure is for three location along the depth of the anchor bolts, where each location represents the average of three readings. From the analysis of the presented result is was

Table 1 Pull-out Strength & Rebound Readings for 12 mm Φ Bolt with Embedment Length of 50 mm

Bolt No.	Rebound Value (R)					Avg. (R)	Pull-Str. (KN)	Com.
	1	2	3	4	5			
1	60	61	58	58	66	60.6	34.45	
2	52	66	49	64	65	59.2	30.54	
3	52	60	52	63	56	56.6	32.30	** *IL*
4	42	50	50	44	44	46.0	27.60	** *IL*
5	58	58	62	52	62	58.4	32.89	
6	52	54	55	58	61	56.0	31.47	** *IL*
7	46	56	52	52	50	51.2	30.67	
8	60	50	58	56	52	55.2	32.28	** *IL*
9	54	58	58	60	56	57.2	33.82	
10	59	54	57	58	54	56.4	33.48	
11	60	50	63	49	64	57.2	38.55	
12	62	64	62	62	65	63.0	36.05	
13	58	50	54	58	50	54.0	31.88	
14	60	63	65	65	66	63.8	37.44	
15	60	66	62	58	56	60.4	35.40	** *IL*
16	58	50	62	53	52	55.0	35.15	
17	65	43	60	56	68	58.4	36.97	
18	58	61	60	61	58	59.6	34.50	** *IL*
19	58	52	54	56	52	54.4	33.31	
20	63	56	57	60	49	57.0	32.89	

** *IL* - Non-vertical anchor bolts with ill-alignment less than 10^o and porous quality of bond between concrete and bolt

noticed that cube specimens number 3, 4, 6, 8, 15 and 18 depict higher ultrasonic wave transit time. Furthermore, the analysis of data presented in Table 1 shows that these specimens also depict a large variation in rebound value. One important observation during the experimentation was that the UPV reading close to the surface of the cube results in the slowest time. This phenomenon can be attributed by improper compaction of the surface layer of concrete since majority of water and air bubbles are present near the concrete surface. Further analysis of the presented data reveals that anchor bolts which show a slower wave propagation correspond also the lower Schmidt hammer rebound number. These two set of indicators can be used to identify anchor bolts with lower pull-out load carrying capacity.

Fig. 11 shows the pull-out strength versus the Schmidt hammer rebound number. From the presented result it can be seen at the Schmidt hammer rebound number, R, increases the pull-out loading carrying capacity, P, also increases. However, there exists a clear range starting from 50 to the peak value near 65. The bolts situated at the lower spectrum represent the bolts with slight ill-alignment. The analysis of the presented data also reveals that the faculty bolts depict a much lower pull-out strength and hence were ignored in the presented data of Fig. 11. Thus, in light of the above-mentioned discussion it can concluded that it is to

Table 2 Ultrasonic Pulse Velocity Readings for 12 mm Φ Bolt with Embedment Length of 50 mm & 70 mm

Bolt No.	50 mm			70 mm		
	Avg. Time (μs)	Avg. Vel. (m/s)	Co.	Avg. Time (μs)	Avg. Vel. (m/s)	Co.
1	31.32	4788.89		30.24	4960.11	
2	30.89	4855.78		31.07	4828.33	
3	31.63	4741.78	**	30.90	4854.78	
4	31.79	4718.33	**	30.81	4868.56	**
5	31.39	4778.44		30.61	4900.22	
6	31.80	4716.98	**	30.53	4912.44	
7	31.39	4779.33		30.93	4848.89	
8	31.73	4727.00	**	31.01	4837.78	
9	31.40	4777.67		30.90	4854.00	
10	31.53	4756.89		31.00	4838.89	
11	30.97	4843.56		31.10	4824.00	**
12	31.41	4775.22		30.64	4896.11	**
13	31.50	4761.90		31.32	4788.00	
14	31.49	4764.00		30.90	4856.67	**
15	31.74	4725.89	**	31.09	4826.44	**
16	31.39	4779.22		30.69	4887.78	
17	31.32	4790.22		30.76	4877.11	
18	31.70	4732.44	**	30.50	4917.89	
19	31.31	4790.44		30.73	4880.67	**
20	30.88	4858.56		30.77	4875.44	**

** Slower ultrasonic pulse velocity transit time result in lower pulse transit time

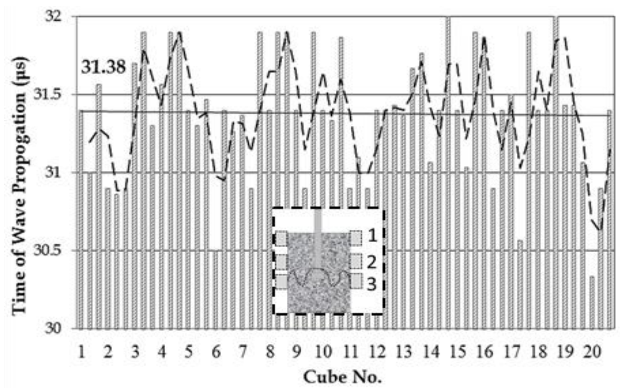

Fig. 10 Variation in ultrasonic pulse velocity along the embedment depth of anchor bolt for 12 mm Φ anchor bolt with embedment length of 50 mm

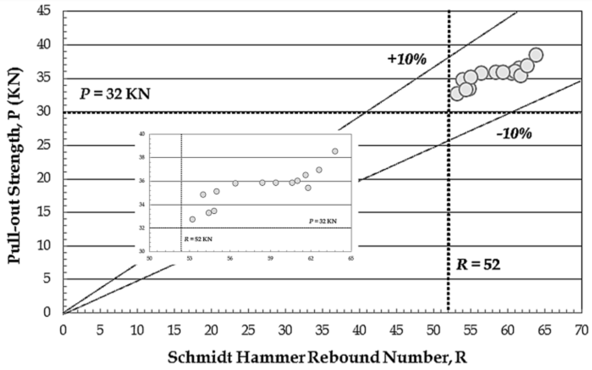

Fig. 11 Pull-out load versus rebound number relationship for 12 mm Φ anchor bolt with embedment length of 50 mm

Table 3 Pull-out Strength & Rebound Readings for 12 mm Φ Bolt with Embedment Length of 70 mm

Bolt No.	Rebound Value (R)					Avg. (R)	Pull-Str. (KN)	Com.
	1	2	3	4	5			
1	44	56	60	58	62	56.0	47.97	
2	55	62	62	60	60	59.8	49.87	
3	58	60	58	63	48	57.4	51.66	
4	42	40	50	60	62	50.8	45.12	** *IL*
5	53	60	64	66	61	60.8	50.34	
6	52	65	65	64	63	61.8	51.94	
7	58	64	55	61	60	59.6	49.07	
8	55	60	58	60	59	58.4	50.83	
9	57	62	64	62	67	62.4	52.85	
10	55	62	62	64	64	61.4	49.86	
11	60	52	58	63	65	59.6	58.64	** *IL*
12	62	62	62	58	62	61.2	46.50	** *IL*
13	55	58	60	58	60	58.2	49.72	
14	60	65	66	65	68	64.8	45.63	** *IL*
15	58	63	64	65	65	63.0	39.92	** *IL*
16	60	60	62	59	64	61.0	49.67	
17	58	58	62	62	54	58.8	50.92	
18	54	63	67	66	65	63.0	52.76	
19	62	64	62	58	66	62.4	47.97	** *IL*
20	54	61	64	66	63	61.6	44.81	** *IL*

** *IL* - Non-vertical anchor bolts with ill-alignment less than 10º and porous quality of bond between concrete and bolt

possible to identify anchor bolts with lower pull-out load carrying capacity by combining the UPV test readings with the Schmidt hammer rebound number. Furthermore, Schmidt hammer rebound number, R of 52 can be treated as cutoff number below which anchor bolts with 12 mm Φ having an embedment length of 50 mm cannot be relied upon for large load carrying capacity. Table 3 presents the result of Schmidt hammer rebound testing for 12 mm Φ bolt with a 70 mm embedment length. Table 2 presents the results of ultrasonic pulse velocity testing for the same anchor bolts.

From the analysis of results presented in the Table 3 and 2 the researcher was successfully able to identify seven faulty anchor bolts which resulted in lower pull-out load carrying capacity. The methodology involved in identifying faulty anchor bolts is based on the rational, as presented in Fig. 6, that UPV velocity is faster in the solid medium as compared to a porous medium, furthermore the ultrasonic pulse travels faster through the steel anchor bolt as compared to the concrete. Thus, by testing the ultrasonic pulse transit time perpendicular to the anchor bolt

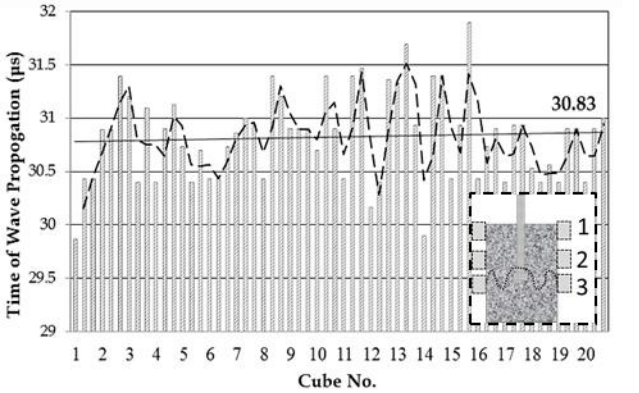

Fig. 12 Variation in ultrasonic pulse velocity along the embedment depth of anchor bolt for 12 mm Φ anchor bolt with embedment length of 70 mm

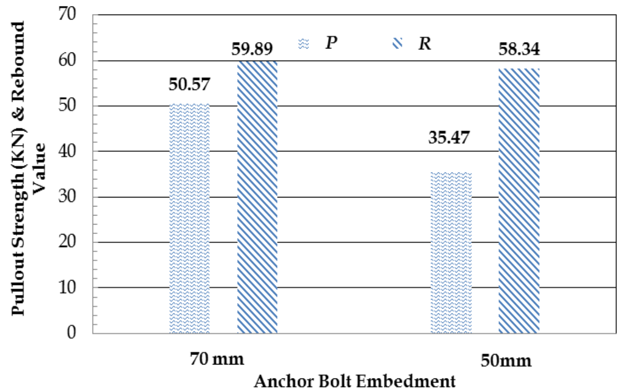

Fig. 14 Average pull-out load versus rebound number comparison for 12 mm Φ anchor bolt

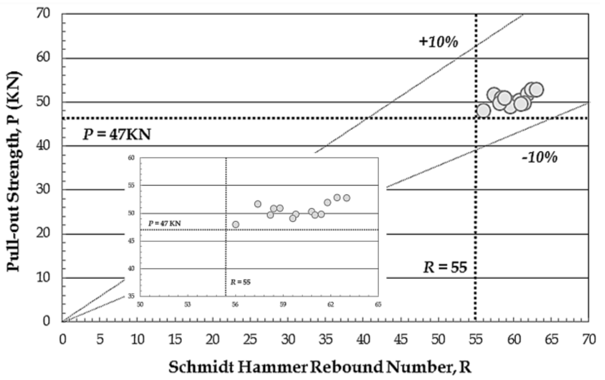

Fig. 13 Pull-out load versus rebound number relationship for 12 mm Φ anchor bolt with embedment length of 70 mm

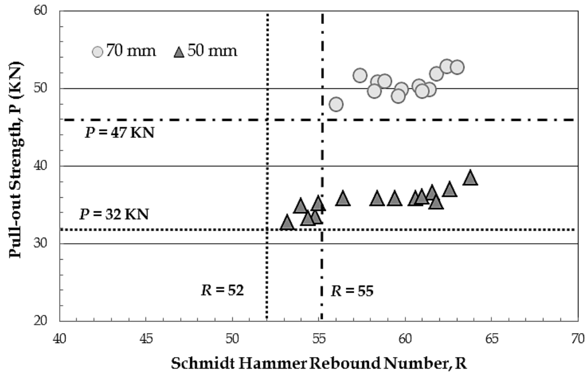

Fig. 15 Combined pull-out load carrying capacity versus Schmidt hammer rebound number

embedment length the researcher can identify bond quality of anchor bolt. Since the anchor bolts with good bond quality exhibit faster wave transmit time as compared to anchor bolts with porous bond the researcher can use this data to pinpoint anchor bolts with poor bond quality. It is known from past published research (Saleem *et al.* 2016) that anchor bolts with lower pull-out load carrying capacity exhibit lower rebound number, the reasoning behind this phenomenon is as explained in the previous section. Thereby relating the UPV test results to the lower average Schmidt hammer rebound number the researchers were successfully able to pin-point faulty anchor bolts.

Fig. 12 presents the UPV testing result for anchor bolts with 70 mm embedment depth. Three reading spots were selected along the embedment depth as shown in the Fig. 3 and three readings were taken at each location. The Fig. 12 presents average of three readings. It can be seen from the presented result that bolt number 4, 11, 12, 15, 16, 19 and 20 all have the UPV readings above the mean average value. This indicates that the bond quality for these bolt elements is porous since the ultrasonic pulse wave takes a longer time to transit the same path length. For several bolt elements the UPV readings near the surface are slower, this erroneous reading can be explained by the presence of air bubbles near the surface layer, which is responsible for delay in transit time of ultrasonic pulse. Table 3 depicts the pull-out load carrying capacity versus the Schmidt hammer rebound number. It can be seen that for the abovementioned anchor bolts there exists a large variation in the Schmidt hammer rebound number. This acts as a verification of the findings of UPV testing. From Fig. 13 it can be seen that there exists a clear cut-off rebound number, *R* of 55, for which a minimum of 47 KN pull-out strength can be achieved. Hence, it can be said that rebound number of 55 can be treated as a cut-off below which bolts with 12 mm Φ bolt having an embedment length of 70 mm cannot be relied upon for large load carrying capacity. Fig. 14 presents the results of average pull-out strength and average rebound number. From the result it can be seen that although the average rebound number *R* is almost the same for anchor bolt with 50 mm and 70 mm embedment length. The corresponding pull-out load carrying capacity for 70 mm embedment length anchor bolts is 29.9% higher than the 50 mm embedment length. Hence, it can be concluded that for the same anchor bolt diameter, the pull-out strength for the larger embedment length is greater than the pull-out strength for the smaller embedment length.

Fig. 15 presents the combined pull-out load carrying capacity versus the Schmidt hammer rebound number. From the presented result it can be seen that their exist a clear range of rebound number for 50 mm embedment length and 70 mm embedment length. Anchor bolts with ill-alignment, porous bond, improper embedment depth can be identified using the rebound number as they depict a rebound number below the specified cut-off value.

Furthermore, as the embedment depth increases the load carrying capacity increases. In-addition the UPV test acts as a confirmation tool to identify anchor bolts with poor installation.

5. Conclusions

An experimental investigation detailing the use of ultrasonic pulse velocity test and Schmidt hammer rebound test to identify anchor bolts with poor bond quality and reduced pull-out load carrying capacity is presented. From the presented results and discussion, the following conclusions can be derived as detailed below;

1. Ultrasonic pulse velocity test combined with Schmidt hammer test can be used to successfully identify faulty anchor bolts with porous bond. Anchor bolts with poor bond exhibit lower rebound number, *R*, and a longer ultrasonic pulse transit time.
2. It is seen during experimentation that anchor bolts with ill-alignment and porous bond cannot be relied upon for higher pull-out load carrying capacity. Furthermore, using the presented methodology, it is possible to pin-point anchor bolts with reduced pull-out load carrying capacity using non-destructive testing.
3. Rebound number, *R* of 52 for 32 KN pullout strength and 55 for 47 KN pullout strength can be treated as a cut-off value for anchor bolts of 12 mm Φ with embedment length of 50 mm and 70 mm, respectively. Anchor bolts which display rebound number lower than the specified values cannot be relied upon for large load carrying capacity.

6. Range of application

The manuscript details a new innovative use of ultrasonic pulse velocity test combined with the Schmidt hammer rebound test to identify the faulty anchor bolts. The provided experimental evidence is for an anchor bolt anchor bolts of 12 mm Φ having an embedment length of 50 mm and 70 mm, respectively embedded in a concrete with average 28 days compressive strength was 34.1 MPa. The maximum size of the coarse aggregate was 19 mm and the ultrasonic pulse velocity testing was conducted on cube specimens with path length of 150 mm after 28 days of curing in a surface dry condition.

The presented research procedure is the first of its kind in terms of non-destructive testing where by combining the UPV test with the Schmidt hammer test, gives engineers/researchers the ability to accurately identify anchor bolts with improper installation, ill-alignment, porous bond or anchor bolts with improper embedment. The development of the proposed procedure of non-destructive investigation can open a new direction for onsite investigation resulting in increased efficiency and accuracy of field measurements.

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PL

Abbreviation

R	Schmidt Hammer Rebound Number
P	Pull-out Load Carrying Capacity
IL	ill-aligned Anchor Bolt
L_d	Embedment Length
L_e	Exposed Length
L_T	Total Length of Anchor Bolt