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Reliability of Non-Destructive Testing Methods in the Assessment of the Strength of Concrete Columns Reinforced with Two Layers of Transverse Confining Stirrups: Empirical Evidence

Mahesh Kumar, S Kaleem Afrough Zaidi, SC Jain and KVSM Krishna

Abstract: Wide spread literature is available on the approach to assess the strength of Reinforced Concrete structures. However no attention has been made so far to study the similar potential when the RC columns are reinforced with double layer of transverse confining stirrups. An obvious reason could be that studies in double layered stirrups options are quite at their infancy. The authors took the advantage of their involvement in studying the axial compression behaviour in terms of strength and ductility of concrete columns reinforced with double layered transverse confining stirrups, applied the two non-destructive measures, viz., Rebound Hammer Test Method (RHTM) and Ultrasonic Pulse Velocity Test Technique (UPVTT), and destructive testing measure, viz., Compression Testing Method (CTM) on the specimens that they have developed in this study. The results have been subjected to regression techniques to build relevant equations for predictability. The present study attempts to explain the detailed procedures adopted within the frame work of the informed knowledge and had attempted to derive meaningful implications for the use of practitioners and academic fraternity. The findings of this paper drew attention to the superior impact of a combined non-destructive testing approach whereby RHTM and UPVTT have been merged in a fashion to yield better assessment of RC columns with double layers of transverse confining stirrups. The combined influence of RHTM and UPVTT clearly explain, greater characteristic compressive strength as one moves from a specimen with a Normal Strength Concrete (NSC) to a specimen with High Strength Concrete (HSC).

Index Terms: Confined Concrete, Non-destructive testing, Rebound Number, Ultra Sonic Pulse Velocity, Empirical non-destructive test model

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I. INTRODUCTION

The uses of non-destructive methods are generally justifiable only if a reliable correlation for a particular type of concrete is developed prior to the evaluation of the quality of subject concrete [1]. Structure health monitoring (SHM) implicates cognitively, the processes of implementing damage deduction and characterization strategies on various structural elements of any edifice beside other structures. In the recent past a rapid constructional development along with a phenomenal rise in the construction of earth quake resistant structures have come up. The reinforced concrete columns confined with two layers of lateral hoops or ties have also been new concepts inferred from recent studies that would enhance the ductility and strength of columns in [2] and [3].

A number of researchers as in [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20] and [21] exercised DT and NDT methods and proposed numerous relationships between the two.

The major research contributions that demonstrate comfortably the possibility of establishing a connection between the destructive and non-destructive approaches of assessing the strength of concrete structures, relatively superior performances of RHT methods and UPVT techniques, and better explain-ability of a combined approach of RHT method along with UPVT technique. Literature has suggested clues on the combining procedure as well. Application on double layered confined concrete structures is non-existents. Understandably, this is due to the relatively recent and new origin of experimental studies in the emerging area. Although a few very fine researchers on assessment of doubly confined concrete columns exists. None of them has applied Non Destructive methods of testing e.g., researches in [3], [22], [23], [24] and [25]. Further the authors' current research provides an opportunity studying the impact upon largest number of samples so far. The researcher has developed 21 numbers of samples of 3 each for a larger study. These samples have come quite handy for conducting the assessment study that the present paper aims at.

The current paper therefore aims at attempting testing experiments on the RC columns with two layered stirrups. The study confines the use of two NDTs, viz. RHTM and UPVTT.

II. RESEARCH OBJECTIVES

The enabling objectives of this research are outlined as under:

1. To find out a characteristic rebound number and ultrasonic pulse velocity of reinforced concrete column specimens confined with double layered stirrups at 90th day of aging of concrete. As guide lines indicate a concrete structure gains up to 95% of its maximum strength after 90 days of its formation, only those specimens are considered which have put up 90 days of life.
2. To study different empirical models that suit for verification of the results.
3. To establish simple and multiple correlation parameters between DT and NDT (linear, nonlinear and multiple regression analysis).
4. To establish a relationship between Non-destructive Testing and Destructive Testing methods for single and double layered confined concrete specimens for normal strength and high strength concretes.

III. EXPERIMENTAL PROGRAM

A. Specimen Preparation

The concrete mixes were designed as per specifications contained in IS: 10262-2009. A total number of 63 RC short column prism specimens were casted and tested under the present investigation. They included 54 numbers of double layered confined specimens and 9 numbers of single layered confined specimens. The specimens were casted and tested in triplicate in order to get the average of three results thus making independent cases of 18 double layers confined concrete columns as well as 3 of single layer confined concrete. The typical specimen reinforcement configurations comprise various forms and shapes of the unconfined and confined specimens.

The double layered stirrups confined concrete specimens were also of the same shape and size as single layered stirrups confined concrete specimens. All the single and double layered confined specimens were cast in four different series, viz., SCCCN, SCCCH, DCCCN and DCCCH. The first four letters in the abbreviations (SCCC) and (DCCC) denote that it is singly or doubly confined concrete column, respectively, and the last letter speaks of the type of concrete mix, i.e., normal grade concrete mix (N) or higher grade concrete mix (H). Each series of the confined specimens possessed same concrete strength but with different attributes in terms of amount, pitch and shape of inner transverse reinforcement, number and amount of longitudinal reinforcement in outer layer, and c/c distance between the inner and outer layers of confining reinforcement.

A lateral concrete cover of 12.5 mm was provided in all the confined concrete specimens along with a cover of 15 mm at the ends of the longitudinal bars at top and bottom surfaces of the specimens to prevent the bars from direct loading. The specimens were cast using wooden formwork in the laboratory following the prevalent practices in construction industry. After 24 hours, the specimens were taken out of the formworks and dipped in water tanks for curing. The curing lasted for 28 days followed by another 62 days of air drying. Thus after 90 days of total ageing, the specimens were put to test under a non-destructive testing approach comprising Schmidt Rebound Hammer and Ultrasonic Pulse Velocity Testing.

B. Non-destructive Testing

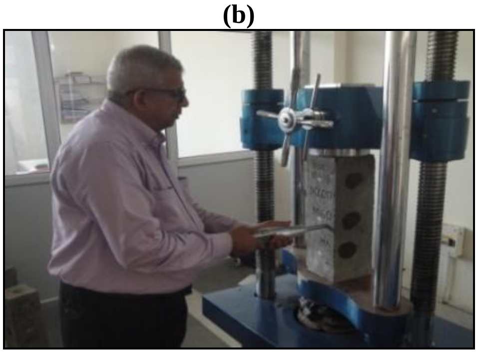
1. Schmidt Rebound Hammer Test

The experimental work was conducted on single and double layered stirrups reinforced concrete columns of Normal Strength and High Strength Concrete. Rebound Hammer and Ultra Sonic Pulse Velocity Tests were performed to obtain results in terms of Rebound Number and Ultrasonic Pulse Velocity. These results were subsequently used to draw correlation curves between the destructive and nondestructive tests. Identification numbers were engraved on the body of the Specimens. N type classic concrete hammer with impact energy of 2.5 N-m was used for non-destructive testing of each specimen. Before putting the specimens to test with Rebound Hammer, the surfaces of the specimens were smoothened by rubbing with abrasive stone.

At the onset, the cubes and specimens were clamped concentrically in the Universal Testing Machine with a constant pressure of the order of 5-7 kN/ mm^2 and thereafter Rebound Hammer Testing was conducted on the specimens as shown in Figure 1 (a), (b) and (c). Furthermore on every specimen, nine impact values were taken and the median values were reported as proposed by IS: 13311.

(a)

(b)



(c)

Fig. 1(a), (b) & (c) Obtention of Rebound Number for NSC and HSC specimens

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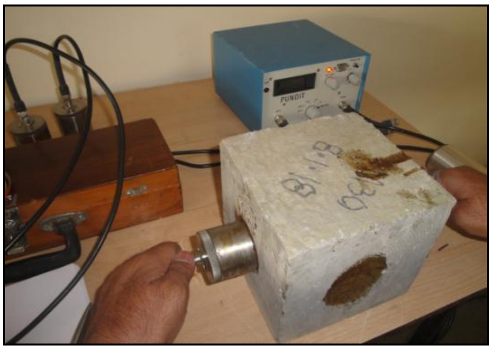
2. Ultrasonic Pulse Velocity Test

Ultrasonic testing equipment included a pulse generation circuit, consisting of electronic circuit for generating pulses and a transducer for transforming electronic pulse into mechanical pulse having an oscillation frequency in the range of 40 kHz to 50 kHz, and a pulse reception circuit that received the signal. Before placing the transducers for measuring the UPV a liquid compiling material such as grease was used as shown in Figure 2. For determining the pulse velocity by direct transmission, two transducers were placed on opposite side of the specimen as shown in Figure 3 (a) & (b).

Fig. 2 Applying grease to ensure adequate acoustical coupling between concrete surface and face of the transducer at points of test



(a)

(b)

Fig. 3 (a) & (b) UPV recording of concrete cube and specimen

The results obtained from the conduction of UPVT were recorded and used in correlating the compressive strengths of the specimen.

3. Destructive testing of specimen

Before mechanical testing of the specimens, a failure test region was forced into the middle 300 mm length of the specimens by providing external confinement in the 75 mm end-regions. The external confinement obtained by fastening the end-regions of the test specimens using 18 mm thick steel collars that prevented an undesirable premature end failure of test specimens to happen. The test specimens were loaded onto a 3000 kN capacity Universal Testing Machine (UTM) blessed with displacement controlled capabilities.

The monotonic concentric compression was applied at a very slow rate to capture clear and complete post peak behavior of the load-deformation curve. Typical Stress-Strain curves apropos destructive testing held for single and double layered concrete specimens (SCCCN1 and DCCCN2) and (SCCCH15 and DCCCH16) of NSC and HSC are depicted in Figure 4 and 5. From the destructive results of specimen it can be seen that with the addition of an inner layer into the specimen, the peak strength and corresponding peak strain increased by 14% and 50%; and 8% and 45% for M30 and M60 grades of concrete, respectively.

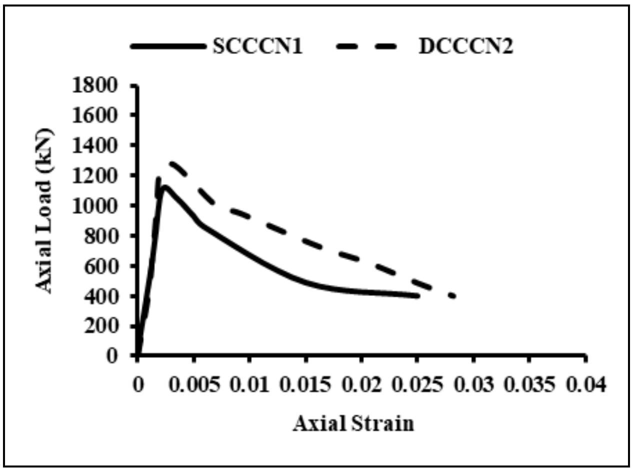


Fig. 4 Comparative Stress-Strain curves (Normal Strength Concrete)

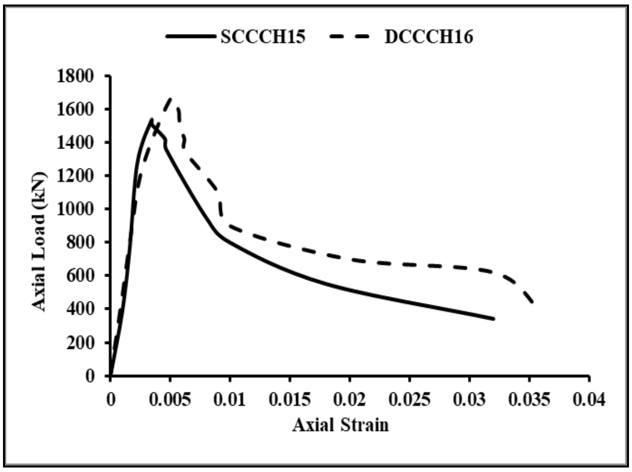


Fig. 5 Comparative Stress-Strain curves (High Strength Concrete)

IV. RESULY ANALYSIS AND DISCUSSION

A. Comparative study of empirical model

A number of nondestructive empirical models that were earlier proposed by innumerous researchers exist in the literature.

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A few relevant empirical relationships emerged from tests using rebound hammer, ultrasonic pulse velocity and a combination of both along with their regression coefficients were presented in Table 1 for the present study. These however have focused on only the single layered structures. An endeavor to correlate RHT and UPVT models on compressive strength of double layered confined concrete columns have been exercised over the models of earlier researchers and shown in Figures 6 and 7, respectively.

An inconsistency in the results of different models can be observed from the graphs shown in Figure 6 and 7. However it is evident that compressive strength of concrete increased with the increase in the value obtained both in the rebound hammer and ultrasonic pulse velocity tests.

Compressive strength determined by exercising rebound hammer models of researchers have been shown in Figure 8, from which it is evident, that despite inconsistency in the results, compressive strength of concrete increased with the increase in the value obtained in numbers from rebound hammer testing for doubly layered transversely confined concrete column specimens.

Compressive strength of concrete versus ultrasonic pulse velocity values have been shown in Figure 9. Substantial variance in the predictions has been observed, but it is also evident that compressive strength of concrete increased with the increase in the value obtained from the ultrasonic pulse velocity tests. It is worth mentioning that these equations were normally used for the predictions of the compressive strength of plain concrete.

It is noticeable from Figures 8 & 9 that these model equations underestimated the strength of reinforced concrete specimen for the grades of concrete used in this study. These equations turned out too conservative since their results lied below the line of equality for this study. The range of the observed differentials which is 20%–30% underestimates between the measured and predicted values. Further investigations needed with greater data to examine and validate the findings in the studies other than those of [6], [9], [11], [16], [19], [20], [21], [26] and [27].

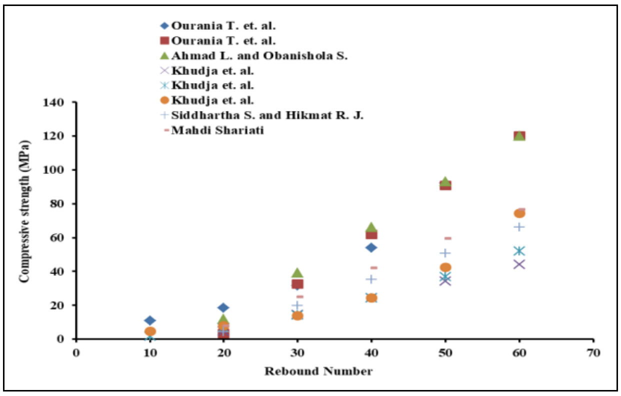

Fig. 6 Calibration data for Rebound Number

Table 1 Empirical relationship of the non-destructive tests

Author/ Year	Equation evaluating f_{cu}	Test Method	R^2	Remark
Ayaz Mahmood (2008)	= 0.008 V + 0.928	UPVT	-	-
Mahdi Shariati (2012)	= 1.7206 R - 26.596 = 15.533 V - 34.358 = - 173.4 + 4.07 V^2 + 57.95 V + 1.31 R	RHT UPVT Combined	-	-
KVR Reddy (2013)	= 83.57 V - 299.3 = 4.443 R - 114.4 = 1.24 R + 0.058 V^2 - 24.1	UPVT RHT Combined	0.990 0.991 0.935	f_{ck} = 50 to 130 MPa
Younes et. al. (2017)	= 0.132 $e^{1.366\ V}$	UPVT	0.950	-
Khudja et. al. (2017)	= - 15.034 * 0.9874 R = 0.0238 $R^{1.8781}$ = 2.6113 $e^{0.558R}$ = - 27.106 + 12.509 V = 0.6401 $V^{2.5054}$ = 1.2288 $e^{0.726\ V}$ = - 24.674 + 0.653 R + 5.572 V = 0.0543 R $V^{1.286}$ = 1.3947 $e^{(0.034\ R)}$ $e^{(0.374\ V)}$	RHT RHT RHT UPVT UPVT UPVT Combined Combined Combined	0.780 0.780 0.770 0.200 0.720 0.720 0.830 0.840 0.840	-
Ourania T, et. al. (2018)	= 6.3715 $e^{0.0534\ R}$ = 2.9168 R - 54.99 = 0.06007 $e^{0.00162\ V}$ = 0.0852 V - 294.24	RHT RHT UPVT UPVT	0.950 0.940 1.000 0.970	Q - value used
Ahmad L, and Obanishola S, (2018)	= 2.7 R - 42 = 9.9 V + 3.7	RHT UPVT	0.916 0.646	-
Akmaluddin et. al. (2018)	= 5.8412 V^2 + 6.946 V - 50.478 = 47.82 V - 1.1 f_c - 79.9	UPVT UPVT for M30	-	f_{ck} = 30 to 60 MPa

Siddhartha S and Hikmat RJ (2018)	= 1.5443 R - 26.579 = 0.0139 V - 30.63	RHT UPVT	0.9566 0.5065	-
Jasim M Abd (2018)	= 320.85l V - 467.73	UPVT	0.900	-

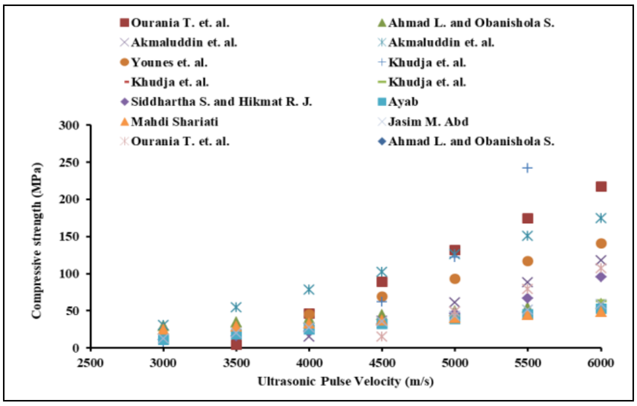

Fig. 7 Calibration data for Pulse Velocity Confined Concrete Column Specimens

B. Nondestructive test results of Double Layered

The compressive strength values as evaluated for double layered stirrup concrete is an average value of the results obtained from tests performed on three specimens. The graphs and values that have been adopted for the comparison of ultra-sonic pulse velocity and rebound hammer test are coping with the results obtained from the destructive testing. The linear and power models between nondestructive testing parameter and two types of concrete and other double layered stirrup confined concrete parameter and their comparisons are described in Tables 2 to 7.

The regression coefficients are determined by the ordinary least squares method. The identified best model must fit the experimental data by obtaining a higher value of the coefficient of determination R^2. The R^2 values range from 0.792 to 0.995 in the present study.

1. Nondestructive test results on plain concrete cubes

Companion standard plain concrete cubes 150x150x150 (mm) were also casted along with each series of specimens to determine the nominal strength of concrete on the day of testing of the test specimens. These cubes, before being put to destructive test, were tested using ultra sonic pulse velocity and rebound hammer testing devices. The average ultrasonic pulse velocity that stood for normal strength concrete cubes (M30 grade) and high strength concrete cubes (M60 grade) were found to be 4.01 and 4.30 km/ sec respectively. In Table 2 the test results of plain concrete cube versus confined concrete specimen have been shown for UPV and RH number.

2. Correlation between the ultrasonic pulse velocities and compressive strengths of Doubly Layered Confined Concrete Column Specimens

Empirical correlations between the results of ultrasonic pulse velocity and compressive strength of confined concrete were developed. Compressive strength of confined concrete is understood and measured as the strength of the concrete specimens measured through destructive approach. Ultrasonic pulse velocity (km/ sec) and compressive strength of confined concrete (MPa), both were measured on the same test specimens and a simplistic analysis has been carried out using software for all the regression models and the best

Table 2 Test results of Ultrasonic pulse velocity and Rebound Number for Cubes and Specimens

Sl. No.	Specimen ID	Ave. UPV for Cube (km/ sec)	Ave. UPV for Specimen (km/ sec)	%age variation	Ave. RH Number for Cube	RH Number for Specimen	%age variation
		A	B	[(B-A)*100]/ A	C	D	[(D-C)*100]/ C
1	SCCCN1	4.01	4.68	16.71	32.76	35.50	8.36
2	DCCCN2	4.01	4.76	18.70	32.76	38.67	18.04
3	DCCCN3	4.01	4.72	17.71	32.76	38.76	18.32
4	DCCCN4	4.01	4.80	19.70	32.76	39.67	21.09
5	DCCCN5	4.01	4.84	20.70	32.76	40.50	23.63
6	DCCCN6	4.01	4.88	21.70	32.76	39.07	19.26
7	DCCCN7	4.01	4.74	18.20	32.76	38.88	18.68
8	DCCCN8	4.01	4.88	21.70	32.76	39.33	20.05
9	DCCCN9	4.01	4.67	16.46	32.76	36.67	11.94
10	SCCCN10	4.01	4.84	20.70	32.76	38.33	17.00
11	DCCCN11	4.01	4.90	22.19	32.76	43.00	31.26
12	DCCCN12	4.01	4.96	23.69	32.76	43.33	32.26
13	DCCCN13	4.01	4.95	23.44	32.76	44.67	36.36
14	DCCCN14	4.01	4.95	23.44	32.76	44.00	34.31
15	SCCCH15	4.30	5.00	16.28	39.87	44.67	12.04
16	DCCCH16	4.30	5.10	18.60	39.87	44.33	11.19
17	DCCCH17	4.30	5.12	19.07	39.87	44.86	12.52

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18	DCCCH18	4.30	5.18	20.47	39.87	44.67	12.04
19	DCCCH19	4.30	5.16	20.00	39.87	47.07	18.06
20	DCCCH20	4.30	5.09	18.37	39.87	44.07	10.53
21	DCCCH21	4.30	5.14	19.53	39.87	44.16	10.76

Table 3 Relationship between UPV and crushing strength of Double Layered Confined Concrete Column Specimens

Types of Models	Expression	Regression Coefficient (R^2)
Linear	f_{cu} = 55.69 V – 211.1	0.890
Exponential	$f_{cu} = 0.881\ e^{0.865\ V}$	0.896
Logarithmic	f_{cu} = 273.9 ln (V) – 373.4	0.885
Polynomial	$f_{cu} = 98.11\ V^2 - 912.8\ V + 2176$	0.931
Power	$f_{cu} = 0.070\ V^{4.257}$	0.892

results thus obtained have been shown in Table 3. The Figure 8 shows graphically the best fit curve indicating compressive strength of double layered confined concrete specimen from the test data.

The best regression curve was established according to the higher coefficient R^2 obtained as 0.931 and as detailed in Table 3. Based on various regressions analysis the polynomial equation between the compressive strength of doubly layered confined concrete and UPV is given by: $f_{cu} = 98.11\ V^2 - 912.80\ V + 2176$, where f_{cu} = strength of confined concrete and V = velocity in km/ sec. The above equation yields R^2 = 0.931. Further it has been observed that, higher the pulse velocity of the test specimen, greater is the compressive strength. The results were found in agreement with the results as shown in Figure 7.

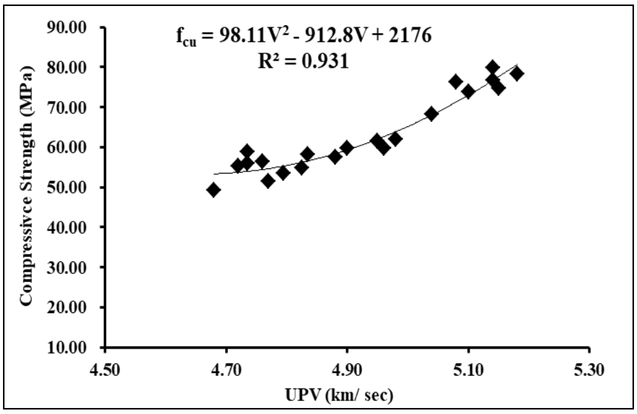

Fig. 8 Correlations curve between Compressive Strength v/s Pulse Velocity for Doubly Layered Confined Concrete Column Specimens

Table 4 Relationship between Rebound Hammer Numbers and crushing strength of Doubly Layered Confined Concrete Column Specimens (f_{cu})

Type of Models	Expression	Regression Coefficient (R^2)
Linear	f_{cu} = 2.592 R – 44.49	0.792
Exponential	$f_{cu} = 11.46\ e^{0.040\ R}$	0.792
Logarithmic	$f_{cu} = 106.1\ l_n\ (R) - 331.9$	0.784
Polynomial	$f_{cu} = 0.143\ R^2 - 9.247\ R + 198.5$	0.808
Power	$f_{cu} = 0.122\ R^{1.673}$	0.814

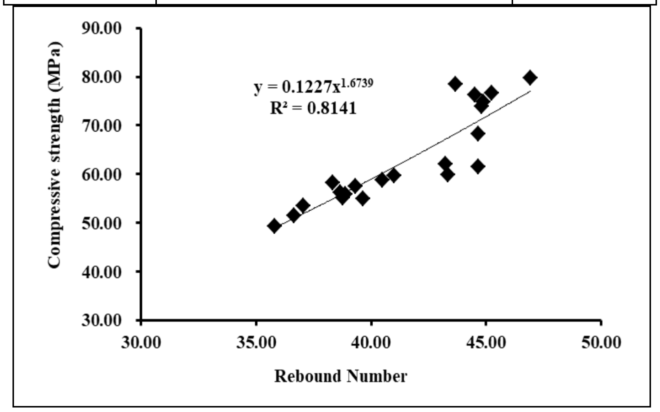

Fig. 9 Relationships between Concrete Compressive Strength and Rebound Number for Doubly Layered Confined Concrete Column Specimens

Table 5 Relationship between Rebound Hammer Number and UPV

Type of Model	Expression	Regression Coefficient (R^2)
Linear	V= 0.109 R + 0.351	0.950
Polynomial	$V = -0.001\ R^2 + 0.193\ R + 0.0030$	0.995

[Where R = Rebound Hammer Number and V = Ultrasonic Pulse Velocity (km/ sec)]

3. Correlation between the rebound hammer number and compressive strength of doubly layered confined concrete column specimens

For developing the relationship between rebound hammer number and compressive strength of confined concrete, average rebound number were calculated. The values with a difference of 5 units or more, if any, from the average, were rejected for this study. The average rebound number and corresponding compressive strength were derived. Linear, exponential, logarithmic, polynomial and power models for the correlation between Rebound Number and crushing strength were established as mentioned in Table 4. Figure 9 shows graphically the best fit curve for indicating concrete compressive strength of double layered confined concrete specimen from the test data. The regression coefficient value (R^2) were found to be better as given by the equation $f_{cu} = 0.122\ R^{1.673}$ in case of Power regression than Polynomial.

The figure shows that Rebound Number increases with increasing the compressive strength of the specimen. Where f_{cu} = compressive strength of the confined concrete and R = Rebound Number

4. Relation between rebound number and ultra-sonic pulse velocity for Doubly Layered Confined Concrete Column Specimens

Both the Rebound Hammer Test and Ultrasonic Pulse Velocity Test were conducted and their measurements were applied on the same specimens and places and their observed data were analysed for evolving a relationship between the rebound number and pulse velocity. On the basis of the results worked out, linear and polynomial relationships were developed as shown in Table 5. Further, Figure 10 shows best correlation curve between rebound number and ultrasonic pulse velocity. Both rebound hammer and ultrasonic pulse velocity test results exhibit almost similar trends for all the specimens put to test.

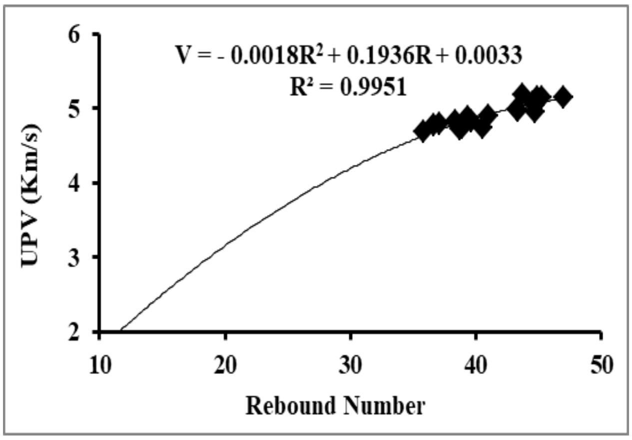

Fig. 10 Correlation curve between Rebound Number and Ultrasonic Pulse Velocity

The regression coefficient values apropos Linear and Polynomial regression analyses, found to be 0.95 and 0.995, respectively, revalidate the results obtained from the tested data. It confirms that these equations can prove to be most reliable models with regard to double layered confined concrete column specimens considered under the present study. Furthermore these equations may also be specifically used to interpret the structural assessment, when only the Rebound Numbers are available. However, higher the Rebound Number, greater is the ultra-sonic pulse velocity in high strength double confined concrete specimens, as expected.

5. Combined relationship between ultrasonic pulse velocity and rebound hammer number (Combined Son-Reb Method)

The term Son-Reb is drawn up by combining terms Sonic and Rebound. In the present cogitation, the results obtained during the destructive testing of specimens were used in order to identify the best fit multiple regression analysis model to ascertain the Son-Reb coefficients. Some research works show that Linear Multiple Regression and Power Multiple Regression can also be used for establishing relationship amongst compressive strength, UPV and/ or Rebound Hammer Number [28] and [29]. In the present study linear and nonlinear regression analyses were also carried out, employing specific expressions as exhibited in Table 6. It has been observed that the regression coefficients thus evaluated best fit the mathematical equations and yield a high value of the determination coefficients (R^2), which indicate the acceptability of this model for predicting compressive strength of concrete for R C Columns compounded with two layers of transverse confining stirrups. Table 6, contains: (i) Linear Multiple Regression and (ii) Nonlinear Multiple Regression model equations for each and all the nondestructive parameters wherein higher numerical value of the regression coefficient forms the basis to be the best fit model among a good many. The results show that the value of R^2 derived from linear multiple regression models and nonlinear models ranged from 0.95 to 0.99 and 0.84 to 0.95 respectively.

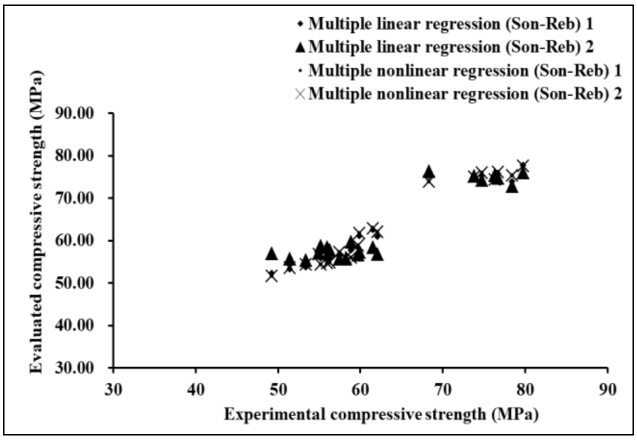

Fig. 11 Comparison between Experimental and Evaluated compressive strengths

These models may be worked out to assess the load carrying capacity of the reinforced concrete columns, provided characteristic compressive strength of concrete (f_{ck} in MPa), ultrasonic pulse velocity in (km/ sec) and rebound number (No.) are known. The combined influence of RHTM and UPVTT explain greater characteristic compressive strength as one moves from a specimen with a Normal Strength Concrete (NSC) to a specimen with High Strength Concrete (HSC). Figure 11, exhibits comparability between (i) strengths derived from the mechanical testing of the specimens and (ii) strength assessed by using best fit mathematical equation.

Table 6 Son-Reb Method (Combined Relationship) Strength of confined concrete (MPa) - Rebound Number (No.) - UPV (km/ sec)

Types of Models	Expression	Regression Coefficient (R^2)
Multiple Linear Regression (Passing through origin)	$f_{cu}1 = 1.17\, f_{ck} - 0.539\, V + 0.42\, R$	0.998
Multiple Linear Regression (Not passing through origin)	$f_{cu}2 = -\, 70.32 + 0.31\, f_{ck} + 18.13\, V + 0.75\, R$	0.950
Multiple Non Linear Regression	$f_{cu}3 = 0.0035\, f_{ck}^2 + 1.6334\, V^2 + 0.00978\, R^2$	0.950
Multiple Non Linear Regression	$f_{cu}4 = 28.4 \ln (f_{ck}) – 102.7 \ln (V) + 33.19 \ln (R)$	0.840

The results shown in Figure 11 indicate that for all the exempla, the values worked out considering the combined Son-Reb methods were found highest to the line of equality for this study of the compressive strength of doubly layered confined concrete columns.

Table 7 Comparison between Predicted & Experimental values

Sl. No.	Specimen ID	Cube Strength of Concrete (MPa)	Compressive Strength of specimen (MPa)	Obtained by UPV (km/ sec)	Predicted Compressive Strength by UPV	%age variation	Obtained RH Number	Predicted Compressive Strength by RH	%age variation	Predicted values by Son-Reb Method							
										Linear Model				Non-Linear Model			
										$f_{cu}1$	% Var.	$f_{cu}2$	% Var.	$f_{cu}3$	% Var.	$f_{cu}4$	% Var.
1	SCCCN1	35.4	49.29	4.68	52.94	-7.41	35.5	50.79	-3.05	53.81	-9.16	52.13	-5.76	52.49	-6.49	61.27	-24.31
2	DCCCN2	35.4	56.31	4.76	54.01	4.09	38.67	55.17	2.03	55.09	2.16	55.96	0.63	56.02	0.52	62.37	-10.76
3	DCCCN3	35.4	55.2	4.72	53.32	3.41	38.76	55.34	-0.25	55.15	0.08	55.3	-0.18	55.47	-0.49	63.31	-14.7
4	DCCCN4	35.4	53.42	4.8	55.01	-2.98	39.67	57.15	-6.97	55.49	-3.87	57.43	-7.5	57.41	-7.47	62.36	-16.72
5	DCCCN5	35.4	58.84	4.84	56.33	4.27	40.5	59.01	-0.28	55.82	5.14	58.78	0.11	58.69	0.26	62.19	-5.69
6	DCCCN6	35.4	54.93	4.88	57.97	-5.52	39.07	55.93	-1.81	55.2	-0.48	58.43	-6.37	58.21	-5.97	60.15	-9.5
7	DCCCN7	35.4	55.96	4.74	53.62	4.17	38.88	55.56	0.7	55.19	1.36	55.75	0.37	55.87	0.16	62.98	-12.56
8	DCCCN8	35.4	57.47	4.88	57.97	-0.87	39.33	56.44	1.78	55.31	3.76	58.63	-2.02	58.41	-1.65	60.37	-5.06
9	DCCCN9	35.4	51.42	4.67	52.9	-2.86	36.67	52.07	-1.27	54.3	-5.6	52.82	-2.73	53.16	-3.38	62.57	-21.67
10	SCCCN10	35.4	58.22	4.84	56.33	3.24	38.33	54.56	6.29	54.91	5.69	57.15	1.84	57.02	2.07	60.36	-3.68
11	DCCCN11	35.4	59.73	4.9	58.9	1.39	43	65.8	-10.16	56.84	4.85	61.74	-3.36	61.69	-3.27	62.91	-5.33
12	DCCCN12	35.4	59.87	4.96	62.17	-3.86	43.33	66.83	-11.64	56.94	4.88	63.08	-5.36	62.93	-5.12	61.92	-3.43
13	DCCCN13	35.4	61.51	4.95	61.58	-0.11	44.67	71.34	-15.98	57.51	6.5	63.9	-3.88	63.92	-3.92	63.14	-2.64
14	DCCCN14	35.4	62.04	4.95	61.58	0.75	44	69.02	-11.24	57.23	7.76	73.29	-18.12	63.34	-2.09	62.63	-0.95
15	SCCCH15	67.3	68.31	5.00	64.75	5.21	44.67	71.34	-4.43	94.55	-38.42	74.7	-9.35	74.81	-9.51	80.35	-17.62
16	DCCCH16	67.3	73.82	5.10	72.56	1.71	44.33	70.15	4.98	94.81	-28.43	76.25	-3.29	76.2	-3.22	78.06	-5.74
17	DCCCH17	67.3	74.76	5.12	74.36	0.53	44.86	72.02	3.66	94.61	-26.56	77.01	-3.02	77.56	-3.75	78.05	-4.41
18	DCCCH18	67.3	78.4	5.18	80.22	-2.32	44.67	71.34	9.01	94.82	-20.95	77.96	0.56	78.35	0.06	76.72	2.15
19	DCCCH19	67.3	79.78	5.16	78.19	1.99	47.07	80.69	-1.15	94.71	-18.72	79.4	0.48	79.2	0.73	78.85	1.16
20	DCCCH20	67.3	76.27	5.09	71.69	6	44.07	69.26	9.19	95.73	-25.52	75.88	0.51	81.01	-6.22	78.07	-2.36
21	DCCCH21	67.3	76.71	5.14	76.23	0.62	44.16	69.56	9.32	94.51	-23.2	55.99	27.01	77.17	-0.59	77.13	-0.55

V. CONCLUSION

This study contemplates a strong correlation between the values in terms of strengths, of double layered stirrups reinforced concrete column specimens, by carrying out destructive and non-destructive tests. On the basis of this investigation following conclusions can be drawn.

1. The uniaxial compressive strength gets increased with the increase in the amount of lateral reinforcement.
2. Concrete may be considered sound and healthy if the pulse velocity measured gives a minimum value of 3.5 km/ second and above. This value is acceptable when lies within the range of 3.5–4.5 km/ second given in the references for all grades of the concrete tested.
3. While validating the compressive strength of double layers confined concrete columns it could be ascertained that non-destructive tests when jointly performed by combining RH and UPV tests yielded more trustworthy test results with enhanced level of accuracy.
4. Several attempts have been made to develop a correlation between compressive strength of concrete specimens and the ultrasonic pulse velocity for RC Columns compounded with two layers of transverse confining stirrups. The best correlation observed has been $f_{cu} = 98.11\, V^2 – 912.80\, V + 2176$, where f_{cu} = strength of confined concrete in MPa and V = ultrasonic pulse velocity in km/ sec, with a value of determination coefficient (R^2) = 0.931. This means that we could clarify 93.1% of the variability for the data around the regression line and 6.9% remained without explanation.

5. Attempts have also been made to develop a correlation between compressive strength of concrete specimens and the Rebound Numbers for R C Columns compounded with two layers of transverse confining stirrups. The best correlation observed has been $f_{cu} = 0.122\ R^{1.673}$, with a value of determination coefficient (R^2) = 0.814. Where f_{cu} = strength of confined concrete in MPa and R = Rebound Number in Nos.
6. On the basis of the experimental study, it has been observed that NDT (RHTM and UPVTT) is reasonably a consummate and dependable method to measure the quality of reinforced concrete in terms of its homogeneity and uniformity which then indicates an acceptability of the quality of reinforced concrete in terms of its strength.
7. The combined influence of RHTM and UPVTT explain greater characteristic compressive strength as one moves from a specimen with a Normal Strength Concrete (NSC) to a specimen with High Strength Concrete (HSC).
8. Linear Multiple Regression and Nonlinear Multiple Regression model equations may be worked out to assess the load carrying capacity of the reinforced concrete columns, provided characteristic compressive strength of concrete (f_{ck} in MPa), ultrasonic pulse velocity in (km/ sec) and Rebound Number (No.) are known.

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