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Bridge Deck Quality Indexing based on Non-Destructive Tests

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Abstract
This paper presents the use of non-destructive tests (NDT) for the assessment of the structural condition of Reinforced Concrete (RC) bridges. Typical damages to in-service concrete bridges include corrosion of rebar, void formation delamination, cracks, wear, and surface blemishes. Detection of the damages is very important to plan a repair and rehabilitation of the bridges to prevent catastrophic failures. In-service RC bridges are selected on the basis of the life served. NDTs, namely the Ultrasonic Pulse Velocity Test (UPVT), rebound hammer test, and electrical resistivity test are used for the determination of structural health i.e. degradation of strength of concrete, the extent of the corrosion, determination of potential voids, cracks, determination of modulus of elasticity. For pilot testing, one of the selected bridges was tested. Based on the different NDT parameters and outputs, a bridge deck quality index is proposed for assessing the condition of RC in-service bridges.

Keywords
Bridges, Non-Destructive Tests, Structural Health

1. Introduction

Bridges form an indispensable part of transportation system. Periodical structural monitoring becomes necessary to rightly catch the deterioration or degradation of the bridges for the effective maintenance, strengthening or repair.Approximately 80% of the bridges in Strategic road network of Nepal are of reinforced concrete types [1]. The focus of this study is to conduct the non-destructive tests (NDT) for the assessment of the structural safety of RCC bridges. Typical damages of in-service concrete bridges include void formation delamination, cracks, wear, corrosion of concrete, surface blemishes which degrades the strength of the concrete.

1.1 Ultrasonic pulse velocity method

The Ultrasonic pulse velocity test method calculates the velocity of ultrasonic pulses through a substance. They are used for detection of cracks or voids. The structural integrity of a concrete part is determined by ultrasonic pulse's velocity through it. Concrete pulse velocity will be higher for good quality of concrete and for poor quality it will be less. The pulse velocity test follows the principal that pulse through any medium depends on the static modulus of elasticity, the cracks and voids, density and homogeneity of the material through it. [2] The quality of concrete in terms of uniformity, can be assessed using the guidelines given in Table 1 .[3]

Table 1: Velocity criterion for concrete quality grading as per IS 13311(Part 1) : 1992

SN	Pulse velocity (km/s)	Quality grading
1	Above 4.5	Excellent
2	3.5 to 4.5	Good
3	3 to 3.5	Medium
4	Below 3.5	Doubtful

The dynamic Young's modulus of elasticity (E_d) of the concrete may be determined from the pulse velocity and the dynamic Poisson's ratio (ν), using the following relationship:

$$E_d = \frac{(1+\nu)(1-2\nu)\rho V^2}{1-\nu} [3]$$

E_d= Dynamic Young's Modulus of elasticity in MPa ρ= density in kg/m3, And V = pulse velocity in m/second. The value of the dynamic Poisson's ratio varies from 0.20 to 0-35, with 0.24 as average. [3] The compressive strength and static modulus of

Table 2: Static modulus of elastic from dynamic elasticity value

SN	Static modulus of Elasticity E_c(GPa)	Literature
1	$E_c = 0.83E_d$	[4]
2	$E_c = 1.25E_d$-19	[5]
3	$E_c = 1.04E_d$ - 4.1	[5]
4	$E_c = \frac{kE_d^{1.4}}{\rho}$	[6]

Table 3: Correlation to compressive strength fc from ultrasonic pulse velocity Vp

SN	Compressive strength fc	Literature
1	$fc = 1.146\exp(0.77Vp)$	[7]
2	$fc = 0.569\exp Vp$	[8]
3	$fc = 8.4*10^-9(Vp)^{2.5921}$	[9]
4	$fc = 0.8822\exp 0.0008Vp$	[10]

elasticity can be determined using different literatures mentioned in Table 2 and Table 3.

To estimate the compressive strength of concrete (MPa) according to the pulse velocity, several relationships have been suggested, one of which is an exponential function as

$$Fc = A\exp^{BVp}$$

1.2 Electrical resistivity test

Another test, Electrical resistivity is used to detect corrosion in reinforced steel concrete. By detecting the potential difference (voltage) between the steel and a half-cell device, which is often constructed of copper or copper sulfate, it detects the corrosion in concrete. By measuring the potential difference between a typical portable half-cell put on the surface of the reinforced concrete deck and the reinforcing steel, it is possible to determine the relative likelihood of corrosion activity [11] In this regard, concrete resistivity is regarded as one of the most significant characteristics that can aid in determining the degree of corrosion of steel in concrete. The apparent resistivity ρ in ohm-cm may be expressed as

$$\rho = \frac{\pi aV}{I}$$

Where V is voltage drop, I is applied current and a is electrode spacing. Various Correlations between ER and probable corrosion are presented by literatures which are illustrated in Table 4 and Table 5.

Table 4: Probable corrosion rate[12]

Resistivity (ohm−m)	Likely Corrosion rate
Less than 50	Excellent
50 to 100	Good
100 to 200	Medium
greater than 200	Doubtful

Table 5: Probable corrosion rate[13]

Resistivity (ohm−m)	Likely Corrosion rate
Less than 50	Excellent
50 to 120	Good
greater than 120	Doubtful

1.3 Rebound Hammer test

This approach, in use since the 1950s, is exceedingly straightforward and user-friendly. The concrete surface is struck with a calibrated hammer, and the amount of rebound is measured. The strength of the concrete that was struck has an impact on the quantity of rebound. However, there is no absolute scale for concrete strength based on the measured rebound due to the considerable heterogeneity of concrete mixes. Therefore, this method is limited to evaluating the relative concrete strength of a concrete bridge. The Schmidt hammer test, which is quick, inexpensive, and non-destructive, is a crucial index test for characterizing rock material. As a result, it is anticipated that the Schmidt hammer test approach will guarantee accurate data collection and analysis both on the job site and in the lab. Without a mushroom plunger (MP) accessory, the experiment detailed below was carried out using SilverSchmidt L.

1.4 Sigmoid function

The sigmoid function is continuously differentiable in the whole function domain and can map the input signal between 0 and 1 in a simple form. The sigmoid function has good properties as an activation function. [14] A sigmoid function is a mathematical function having a characteristic S shaped curve or sigmoid curve. The other commonly used range is from -1 to 1.

2. Research Objectives

The objectives of the research are given below:

- Assessment of the in service bridge structural health using different NDT equipment and technology.
- To propose Bridge quality indexing system on the basis of the results obtained from NDTs.

3. Methodology and Data collection

The methodology is oriented towards the fulfilment of objectives of this research work. The steps to be followed are:

1. Selection of in-service reinforced concrete bridges of Nepal comprising of different age groups (i.e. different life served).
2. Carrying out survey regarding the design, construction and the traffic data at these bridge sites.
3. Determining the critical areas on the bridge where it is highly vulnerable with respect to cracks, delamination, water seepage, corrosion of reinforcement, etc.
4. Carrying out Non-destructive testing with all the mentioned and technologies available in all the bridges selected.
5. Determining the extent of deterioration or degradation on the bridge sites based on NDTs conducted.
6. Quantifying results obtained from NDT and used for input parameter for bridge deck quality indexing.
7. Validating of the indexing system from a previously core cut sample and know exact condition of the bridge deck.

For the achievement above mentioned process the RCC T Beam girder bridge over Dhobikhola River in Kapan, Budhanilkantha municipality and Hanumante bridge in bhaktapur, Madhyapur thimi municipality was selected. The Dhobikhola Bridge was built in four years ago and the span of the bridge is 16m while the Hanumante Bridge was built twenty three years ago according to the public nearby it and the span of the bridge is 24m.

The non-destructive tests namely UPV test, Schmidt hammer test and Electrical resistivity test was done in twenty four points in dhobikhola bridge and twenty points in hanumante bridge across the slab at the two extremities of lane and middle of the lane.In deck of slab only possible configuration of transducer was indirect probing. At each point three data were taken with a path length of 300mm.

4. Bridge Deck Quality index

The results obtained from the all the NDT's conducted are processed to form an index of bridge slab that indicates how much bridge has degraded in terms of its strength and corrosiveness. The process of this indexing involves following steps:

1. The compressive strength (fc) is obtained from Schmidt hammer test and ultrasonic pulse velocity test as in aforementioned literatures.
2. The static modulus of elasticity (Ec) is obtained from the ultrasonic pulse velocity test.
3. Compressive strength ratio ($\frac{fc}{fcp}$), Modulus of elasticity ratio ($\frac{E_c}{E_cp}$) and electrical resistivity (ρ) data are normalized between 0 and 1 using modified using modified sigmoid function.
   Where, fc= compressive strength from NDTs
   fcp = Compressive strength initially(35Mpa)
   E_c=Static modulus of elasticity from NDTs
4. All the normalized values plotted for maximum value to form equilateral triangle of area $3\sqrt{(3)}/4$ square units. The vertex of triangle being the maximum value one in the triangle and the centroid of the triangle being the zero value for each of the parameter as shown in given figure which depicts blue as standard triangle and red triangle signifying actual status of bridge.
5. The smaller triangle depicts the actual status of the bridge.
6. The ratio for area of bigger triangle to smaller triangle is the quality index of the respective bridge representing quality degradation w.r.t strength, corrosion and elasticity values as depicted in Figure 1 .

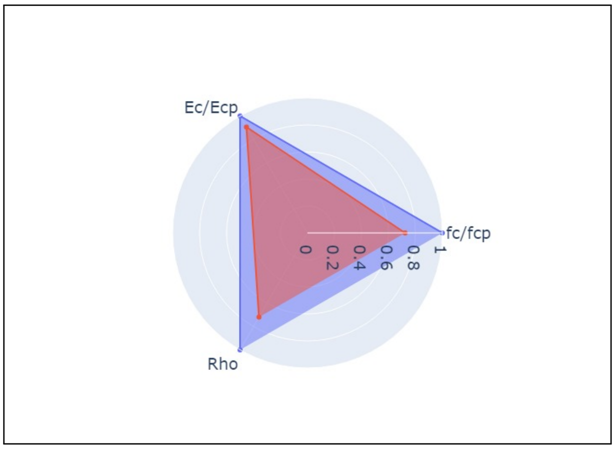

Figure 1: Triangle for quality indexing

5. Results and Discussion

5.1 Dhobikhola Bridge

Ultrasonic pulse velocity test was taken three readings at each point. Ultrasonic pulse velocity was then corrected for surface (indirect)probing [15, 3]. Each velocity is further correlated as mentioned in Section 1.1 to obtain compressive strength and modulus of elasticity at site condition. At each test point ten rebound hammer test were averaged to obtain compressive strength of concrete. At each point three test of Electric resistivity were done to obtain probable corrosion rate. From electrical resistivity test data i.e. from ρ, the corrosion rate is ascertained. These test output are processed to form Bridge Deck Quality Index mentioned in Section 4.
The a quality index in terms strength and corrosion characteristics was found to be having maximum value of 0.871 and minimum value of 0.581.
There were twenty four points which were tested in the dhobikhola slab deck. The parameters compressive strength ratio, Elasticity ratio and resistivity from the conducted NDTs were normalized by sigmoid function as given in Table 6.

Table 6: Normalized parameters $\frac{fc}{fcp}$, $\frac{Ec}{Ecp}$, ρ along with bridge deck quality index froum Rebound hammer test(RHT), Ultrasonic Pulse Velocity test(UPVT) and Electrical resistivity test(ERT).

Test Points	RHT	UPVT	UPVT	ERT	
Parameter	$\frac{fc}{fcp}$	$\frac{fc}{fcp}$	$\frac{Ec}{Ecp}$	ρ	Quality index
1	0.81	0.84	1.07	183	0.871
2	0.87	0.87	1.11	222	0.904
3	0.5	0.45	0.63	194	0.67
4	0.73	0.56	0.78	153	0.754
5	0.67	0.71	0.95	124	0.753
6	0.7	0.73	0.97	86	0.668
7	0.84	0.98	1.2	96	0.752
8	0.4	0.6	0.82	99	0.609
9	1.09	0.6	0.82	131	0.781
10	0.75	0.72	0.95	134	0.783
11	0.65	0.66	0.89	160	0.784
12	0.68	0.59	0.81	171	0.774
13	0.95	0.82	1.06	146	0.843
14	0.94	0.62	0.85	101	0.71
15	0.91	0.73	0.97	57	0.581
16	0.61	0.71	0.95	158	0.792
17	0.62	0.6	0.82	263	0.805
18	0.56	0.55	0.77	150	0.713
19	0.49	0.62	0.85	138	0.713
20	0.66	0.76	1	95	0.697
21	0.71	0.69	0.93	99	0.697
22	0.78	0.83	1.07	166	0.852
23	0.69	0.59	0.82	119	0.709
24	0.59	0.64	0.87	164	0.771

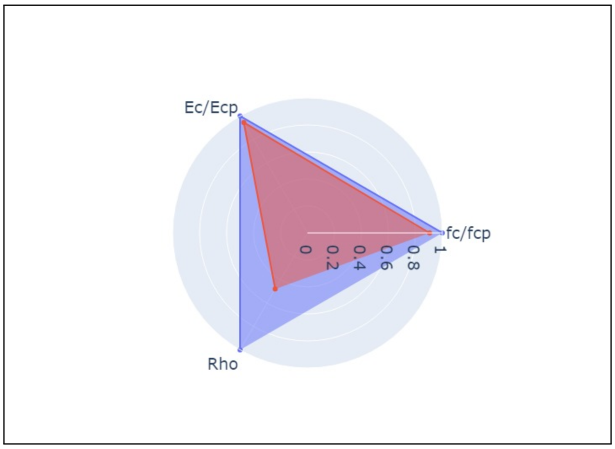

Figure 2: Minimum value of index at NDT point no.15 INDEX=0.581 (at the 7.5 from the Sukedhara side)

5.2 Hanumante Bridge

The quality index in terms strength and corrosion characteristics was found to be having maximum value of 0.628 and minimum value of 0.39. There were twenty points which were tested in the slab deck. The parameters compressive strength ratio, Elasticity ratio and resistivity from the conducted NDTs were normalized by sigmoid function as given in Table 7.

The minimum and maximum index in Dhobikhla Bridge are shown in Figure 2 and Figure 3

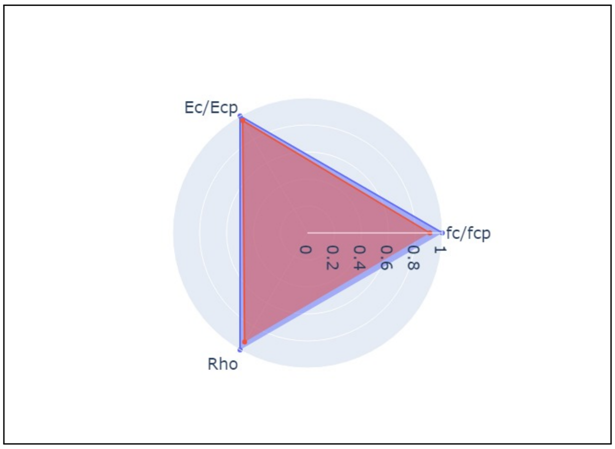

Figure 3: Maximum value of index at NDT point no.1 INDEX=0.871 (at the 1.5 from the Sukedhara side)

Table 7: Normalized parameters $\frac{fc}{fcp}$, $\frac{Ec}{Ecp}$, ρ along with bridge deck quality index froum Rebound hammer test(RHT), Ultrasonic Pulse Velocity test(UPVT) and Electrical resistivity test(ERT).

Test Points	RHT	UPVT	UPVT	ERT	
Parameter	$\frac{fc}{fcp}$	$\frac{fc}{fcp}$	$\frac{Ec}{Ecp}$	ρ	Quality index
1	0.61	0.5	0.7	87	0.578
2	0.45	0.43	0.61	81	0.489
3	0.41	0.4	0.57	107	0.506
4	0.59	0.75	0.99	73	0.615
5	0.54	0.4	0.57	64	0.44
6	0.5	0.48	0.68	121	0.62
7	0.43	0.39	0.55	67	0.417
8	0.5	0.41	0.57	71	0.456
9	0.55	0.43	0.6	124	0.601
10	0.59	0.46	0.65	57	0.458
11	0.63	0.52	0.73	67	0.529
12	0.66	0.33	0.45	86	0.468
13	0.58	0.46	0.64	90	0.557
14	0.66	0.41	0.57	132	0.623
15	0.52	0.45	0.54	51	0.393
16	0.57	0.75	0.98	78	0.628
17	0.64	0.43	0.61	56	0.448
18	0.72	0.32	0.38	66	0.39
19	0.61	0.74	0.98	138	0.775
20	0.66	0.31	0.43	45	0.334

The minimum and maximum index in Dhobikhla Bridge are shown in Figure 4 and Figure 5

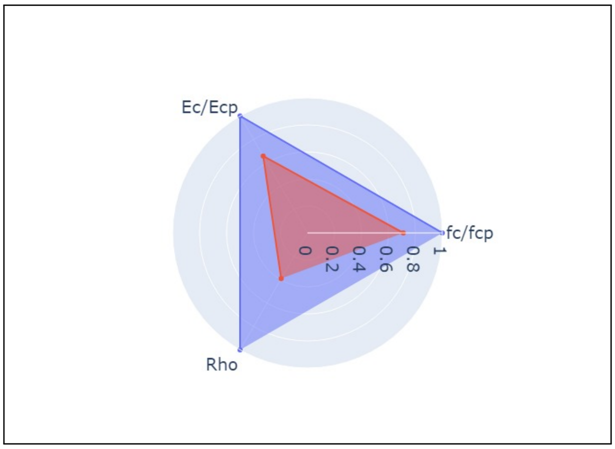

Figure 4: Minimum value of index at NDT point no.18 INDEX=0.39 (at the 10.5m from the tikathali side along central line)

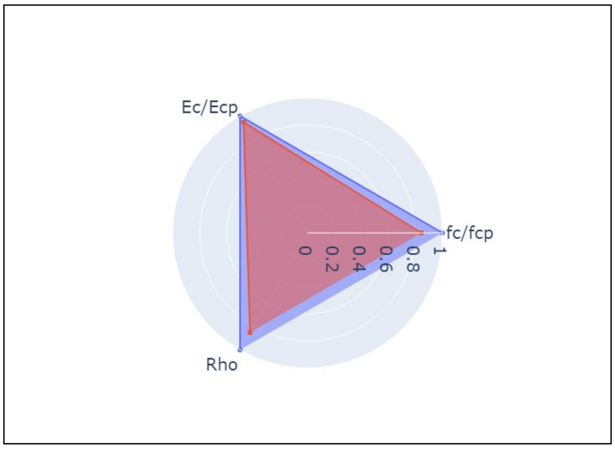

Figure 5: Maximum value of index at NDT point no.16 INDEX=0.628 (at the 3m from the tikathali side)

6. Conclusions

6.1 Discussions

Bridge deck Quality index (BDQI) that has been generated in this thesis work represents the degradation of slab deck and slab deck only. The values given by BDQI does not correspond to the values given by quantitative damage assessment given by prevailing codes and should only be compared with other BDQI values. Tests for other components of bridge such as Piers, Girders, rebar, etc. and seismic aspect can further be incorporated into the polygon to give comprehensive image about the quality of bridge.

6.2 Validation

The test conducted in a bridge in Telangana [16] conducted test and core sample data of a bridge constructed 35 years ago. The accuracy obtained between them was 86.54%. The accuracy could have been even better if we conducted core sampling in Kathmandu valley.

6.3 Dhobikhola Bridge

1. The bridge deck quality index over 24 points was found with minimum value of 0.581 around mid-span (test point 15) where there is maximum deflection and maximum dynamic load impact.
2. The high value of pulse velocity means that the concrete has very low amount of cracks, voids and delamination in it. From NDT's probable corrosion rate is negligible as confirmed by Indexing. Further it can be supported by the fact that the bridge is new one which was in service for only four years.

6.4 Hanumante Bridge

1. The bridge deck quality index over 20 points was found with minimum value of 0.39 at 10.5m from the tikathali side. (NDT point 18). The bridge was constructed twenty three years ago according public near the site.
2. The pulse velocity and rebound hammer shows that the strength has degraded static modulus of elasticity was found to be decreased which can be further supported by indexing. The Corrosion rate of concrete is very high as obtained from the resistivity data.

6.5 Limitations of the research work

1. Only the slab part of bridge is under research work.
2. There are only three quality index parameter of bridge. The numbers of side can be increased from triangle to polygon by introducing new parameters and tests.
3. The importance factor to a particular test is not determined and a regular polygon for quality indexing is formed.
4. All the tests are given equal importance.
5. Repairing techniques of the specific damages are out of scope of this study.

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