



A practical approach to determine the depth of neutral axis of a RC flexural member

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Abstract : A flexural R.C. member, designed either with working stress method or limit state method, is placed in position either by cast in-situ or precast method. At the time of construction as the member is erected as per design specifications, its materials as well as cross-sectional properties are well defined and known. Hence two key design parameters viz. depth of neutral axis and moment of resistance, are well known. With passage of time, the member/structure ages and these properties may change. There is also a possibility that the member/structure may be subjected to different loading conditions than what it was originally designed for. Temporal evolution results in loss of basic data of the structure related to the original and current usage as well as loading pattern. Furthermore, a RC member is a composite member composed of concrete and steel. For most of old age structures, basic quality governing parameters and test results are not available.

Thus, determination of basic design parameters and cross-sectional properties of an old age RC member or structure becomes a challenge. Neutral axis of a flexural member plays a key role in its design. If someone succeeds in determining the depth of neutral axis of an in-situ flexural member, it will be possible to determine its other design parameters and member. A practical solution in this direction is presented here to locate the depth of neutral axis.

Key words :- Depth of Neutral axis, Moment of resistance , Nondestructive testing , Strain.

1. INTRODUCTION

Invention of concrete and further its development into reinforced concrete met the housing, commercial and infrastructural requirements of the growing population after the Second World War. The development of working stress method, ultimate load method and limit state method enabled to construct multistoried buildings and increased span for bridges breaking the limitations of masonry and combined wood structures. In India after independence, major infrastructural development was initiated by the government. Initially major buildings and bridges were constructed in masonry especially with arch structures. In the late '60s RCC construction became popular and old constructions were extended with RC construction. Use of pre-stressed concrete started in early '80s. At present, the extensions to the bridges, executed in late '70s, are about 40 to 50 years old which is almost half of their expected age. A major investigation of bridges from the city of Ahmednagar to Tembhorni village stretch of NH 561A was carried along with some non-destructive testing like rebound hammer test, ultrasonic pulse velocity, etc. During inspection it was found that basic quality control data like mix design, cube testing, slump, beam testing, reinforcement steel manufacturers and lab test reports, etc. of concrete and steel was not available. Also working structural drawings were not available. As many structures have passed their mid-life, it is necessary to evaluate their residual life. Now in absence of basic material specifications, properties and initial test results; the possibility to find out their present properties without disturbing the structure is a challenge.

2. IMPORTANCE OF IN-SITU PROPERTIES OF CONCRETE

Performance of a structure is mainly affected by the properties of ingredient constituents and environmental impacts on it. Structures designed with common material properties may show different in-situ properties with passage of time, if subjected to different environmental conditions and loading patterns. Proper assessment of in-situ properties of a structural member will help to predict the serviceable condition and thereby avoiding the possibilities of failure. In case of infrastructural elements, especially for bridges and flyovers, investigation of in-situ properties will help in taking proper and in time decisions regarding repairs and replacements such as imposing traffic limitations like barring heavy vehicles or imposing speed limit, traffic diversions, immediate repair measures and replacement alternatives etc.

Bridges form an important organ of communication infrastructure. In most of the cases bridges and flyovers are constructed with long spans. As compared to flexural members in buildings, deflection of flexural members in bridges and flyovers are predominant and easy to record.

2. METHODS FOR DETERMINATION OF IN-SITU PROPERTIES

Various non-destructive tests are developed so as to access the in-situ properties of concrete. These tests are used to estimate the structural properties of concrete especially the characteristic strength. The main drawback of these tests is that they cannot comment on moment of resistance of the flexural member. The ultrasonic techniques are mainly suitable for detecting invisible surface defects, estimating the depth of crack, determining the dimensions of elements accessible from one side only and 2D and 3D imaging of reinforcement distribution [8]. The most popular tests include ultrasonic pulse velocity, rebound number, probe penetration (Windsor probe), pullout, break off, core drilling and maturity etc. The bureau of Indian Standards published standards for ultrasonic pulse velocity test vide IS- 13311 Part 1[2] and for rebound hammer test vide IS- 13311 Part 2[3]. Only these two tests are included in the Indian Standards. Besides these two, other tests like penetration resistance, break off, CAPO etc. are also used widely and recommended by other standards. All the non-destructive test methods, popularly abbreviated as NDT, are based on some specific principles and the test results are correlated to the characteristic strength of in-situ concrete. Some widely used tests are enlisted below.

i) Ultrasonic Pulse Velocity Test: - It is based on the principle that the velocity of a pulse through a medium is independent of the geometry and depends only on its elastic properties. The table 2 of IS- 13311, part 1[2], specifies velocity criterion for concrete grading depending upon pulse velocity by cross probing in km/s; with concrete grading as excellent, good, medium, doubtful etc. The clause 7.4 provides an equation to calculate the dynamic Young's modulus.

ii) Rebound Hammer Test :- The part 2 of IS- 13311[3], deals with rebound hammer test. It is based on the principle that the rebound of a spring-controlled mass depends upon the surface hardness of concrete and therefore the rebound is taken. The rebound number is correlated with characteristic strength of concrete.

iii) Penetration Resistance Test (Windsor Probe Test) [7] :- The test was developed in USA during mid-sixties. It is also known as Windsor Probe Test. In this method a plunger of specific diameter and length is penetrated in concrete surface with known defined force and length outside the concrete surface is measured. It is one type of hardness testing and measurements are related to the characteristic strength of concrete.

iv) Break off Test[9] :- The test is based on breaking off a cylindrical specimen of in-situ concrete. A testing sleeve is embedded in wet concrete and force required to break off the sleeve is measured and is correlated with the characteristic strength of concrete.

v) CAPO Test :- The Cut And Pull Out test is another method used to determine in-situ compressive strength of various structures like concrete roads, bridges, buildings etc. It consists coring a 18.4 mm diameter hole, perpendicular to the surface of concrete. A slot of 25 mm in diameter and 25 mm in depth is recessed in the hole. A split ring is expanded in the recess so carved and pulled out against a 55 mm diameter counter ring using a pull machine. The ultimate pullout force is correlated directly to the compressive strength of concrete. The test is recommended by Central Road Research Institute (CSIR)^[6] and also is included in ASTM C-900-6^[4] and EN 12504.3. The measurements of the test are correlated with the characteristic strength of concrete.

4. LIMITATIONS OF EXISTING NON-DESTRUCTIVE TESTS

i) Ultrasonic Pulse Velocity Test :- The IS 13311 (Part 1) [2] underlines the limitations of the test vide clause 7.2 stating that " ...the criterion specified in Table 2 of the code can be held as satisfactory only to a general extent ..." Also, the clause 7.3 denies the adequacy of compressive strength on the basis of the test because of the lower statistical confidence of correlation between the two. The code also states the variation limit of estimated strength to the actual strength as 20 %.

ii) Rebound hammer Test :- There are many factors that influence the results of the rebound hammer test. The clause 7 of the IS 13311 (Part 2) [3] describes various factors influencing the rebound hammer number such as types of cement and aggregate, moisture content and surface conditions, age of concrete and extent of carbonation etc. Due to these factors, at clause 8.1, the code itself accepts as "... the probable accuracy of prediction of concrete strength in a structure is 25 %"

iii) Penetration Resistance Test :- As the method involves penetrating a plunger of specific diameter and length, the test results specifically represent the characteristics of surface concrete. Also the results are location specific. Hence the results do not represent the characteristics of a member as a whole.

iv) Break Off Test :- As the test needs embedment of testing sleeve in wet concrete, it is useful for fresh concrete. For old age structures and already casted members or structures it is not applicable.

v) CAPO Test :- The Cut And Pull Out test fetches a concrete sample from the 50 mm depth of concrete member. In case of small members like beams and slabs in a buildings structure it is difficult to get reinforcement free a location up to a depth of 50 mm. Also, the results are location specific and may not represent the characteristics of the member as a whole.

5. ADDITIONAL REMARKS ON LIMITATIONS OF NDT

All the above discussion reveals that the nondestructive test so far available has advantages as well as limitations of their own. Besides their limitations in methodology and reliability, they represent only location specific properties of an in-situ member. Now a day, it has become mandatory to monitor the in-situ properties of a structure for a long time. All the above nondestructive tests may prove to be uneconomical and time consuming in the era of latest technology and advances in computer data logging and remote sensing. With the help of the latest technology, it is possible to monitor member specific and time specific in-situ properties of a structure. Hence it is envisaged a need of a method that will determine the in-situ properties of a member removing the disadvantages or lacunas in the present testing methods.

6. ROLE OF MODULUS OF ELASTICITY

In any structure, flexural members are more susceptible to deterioration as tension is introduced due to bending action which has tendency of splitting. In such members, cracks are developed in tension zone under the action of external loads as well as self-weight. These cracks permit the ingress of carbon dioxide and chloride attack which finally results in carbonation of concrete and corrosion of the reinforcement. It is a question whether the properties like modulus of elasticity (E) and characteristic strength (f_{ck}), changes with time or not. In-situ investigation of modulus of elasticity of concrete member is difficult as a flexural member is a composite structure. To check the serviceability of a flexural member, it is a common practice to calculate the theoretical values of deflections and compare them with the limits as per the standards.

7. CODAL PROVISIONS FOR MODULUS OF ELASTICITY

As per IS-456^[1], clause 6.2.3.1, the relation between the short-term static modulus of elasticity (E_c) and the characteristic strength of concrete is expressed as,

$$E_c = 5000\sqrt{f_{ck}} \dots \dots \dots (1)$$

The expression for long term modulus of elasticity of concrete is not directly given in IS-456. It is expressed in terms of modular ratio. The IS-456, clause B-1.3 (d) provides following expression for the modular ratio for steel and concrete.

$$m = 280 / (3 \sigma_{cbc}) \dots \dots \dots (2)$$

Where, σ_{cbc} = permissible stress in concrete in bending compression.

The table 21 of IS-456^[1] enlists permissible stress in bending compression for various grades of concrete. It shows that the factor of safety of 3 is used to arrive at the values of permissible stress in bending compression for concrete, i.e., $\sigma_{cbc} = f_{ck}/3$ from this we can say that $f_{ck} = 3\sigma_{cbc}$.

Thus, the equation (2) can be rewritten as

$$m = 280 / (f_{ck}) \text{ or } E_c = E_s f_{ck} / 280.$$

As per Clause 5.6.3 of IS-456^[1] we have $E_s = 2 \times 10^5 \text{ N/mm}^2$. Hence, we can write,

$$E_c = 714.2857 f_{ck} \dots \dots \dots (2A)$$

The clause C-4.1 specifies the effective modulus of elasticity of concrete to determine the deflections due to creep as

$$E_{ce} = E_c / (1 + \theta) \dots \dots \dots (3)$$

where θ = the creep coefficient.

The clause 6.2.5 of IS-456^[1]:2000 specifies values of creep coefficients depending on the age of concrete. These are enlisted in table below.

Table 1- Values of the creep coefficient (θ) as specified in clause 6.2.5.

Age at Loading	7 Days	28 Days	1 Year
Creep Coefficient (θ)	2.2	1.6	1.1

As all the values of the creep coefficient are more than 1, it is evident from equation 1, that values of effective modulus of elasticity of concrete will always be less than half of the short-term modulus of elasticity.

8. COMMENTS ON CODAL PROVISIONS

There are three different clauses that describe the formulae for determination of modulus of elasticity of concrete. The Clause 6.2.3.1 gives the short term modulus of elasticity whereas the clause B-1.3 gives long term modulus of elasticity. The following table shows values of modulus of elasticity calculated from the above three equations.

Table 2 - Calculated values of modulus of elasticity of concrete as per IS 456. ^[1]

f_{ck}	σ_{cbc}	Clause 6.2.3.1 E_c short = $5000 \sqrt{f_{ck}}$	Clause B-1.3 E_c long = $714.2857f_{ck}$	Ratio $\frac{E_c \text{ short}}{E_c \text{ long}}$	Clause C-4.1 $E_{ce} = E_c/(1+\theta)$		
					7 Days $\theta = 2.2$	28 Days $\theta = 1.6$	1 Year $\theta = 1.1$
10	3	15811.39	7142.86	2.21	4941.06	6081.30	7529.23
15	5	19364.92	10714.29	1.81	6051.54	7448.04	9221.39
20	7	22360.68	14285.71	1.57	6987.71	8600.26	10647.94
25	8.5	25000.00	17857.14	1.40	7812.50	9615.38	11904.76
30	10	27386.13	21428.57	1.28	8558.16	10533.13	13041.01
35	11.5	29580.40	25000.00	1.18	9243.87	11377.08	14085.90
40	13	31622.78	28571.43	1.11	9882.12	12162.61	15058.47
45	14.5	33541.02	32142.86	1.04	10481.57	12900.39	15971.91
50	16	35355.34	35714.29	0.99	11048.54	13598.21	16835.88

From the above table it is evident that

A) The value of modulus of elasticity of concrete, calculated as per clause 6.2.3.1 of IS 456-2000^[1], varies drastically from 15811.39 for M-10 to 35355.34 for M-50, as per grade of concrete. The short-term modulus of elasticity for M-50 grade of concrete is almost double as that of M-10 grade of concrete.

B) The long-term modulus of elasticity, calculated as per clause B-1.3 of IS 456-2000^[1], varies from 7142.86 for M-10 to 35714.29 for M-50 grade of concrete, which is almost five times as compared to M-10 grade of concrete.

C) The long-term modulus of elasticity, calculated as per clause C-4.1 of IS 456-2000^[1], varies from 7529.23 for M-10 to 16835.88 for M-50, which 2.23 times as compared to M-10 grade of concrete.

Also, it is to be noted that, as concrete deteriorates with time, consequently its modulus of elasticity may get affected. At the same time, due to application of service loads over a period, its section properties like moment of inertia will also get affected due to development of cracks. For many of old structures, non-availability of basic data is a common problem. The basic data includes section properties, grade of concrete at the time of construction, reinforcement detailing, etc. Due to lack of this information, it becomes very difficult to evaluate present serviceable condition of the member or structure.

To overcome the above situation, we will have to use a term or terms which will represent all the above parameters. The modulus of elasticity and the moment of inertia of a reinforced concrete flexural member are expressed in a term popularly known as flexural stiffness of the member and denoted as EI, where E is the modulus of elasticity and I is the moment of inertia of the section. In design as well as analysis of a flexural member, the depth of neutral axis plays an important role. To find the depth of neutral axis, it is necessary to know the cross-sectional dimensions and reinforcement details especially at bottom and top of the section. But in case of old structures where such data is not available, it becomes difficult to analyze the member and to arrive at a solid conclusion. Now a day some techniques are available to locate reinforcement of a reinforced concrete member, but they prove to be difficult in use for bottom of a bridge member due to more heights and inaccessibility in case of river or valley bridge.

9. NEW APPROACH

To overcome the above-mentioned drawbacks, a new approach is encountered and presented here. Here it is assumed that the geometrical section properties and reinforcement details of the member are not known and hence we cannot locate the position i.e., depth of neutral axis of the flexural member. Following method of measuring strains at two different levels will help to locate the realistic depth of neutral axis. Consider a cross section of a flexural member as shown below. As per IS-456-2000^[1], maximum value of strain in concrete is limited to 0.0035 and that in steel is limited to $[(0.87f_y/E_s)+0.002]$.

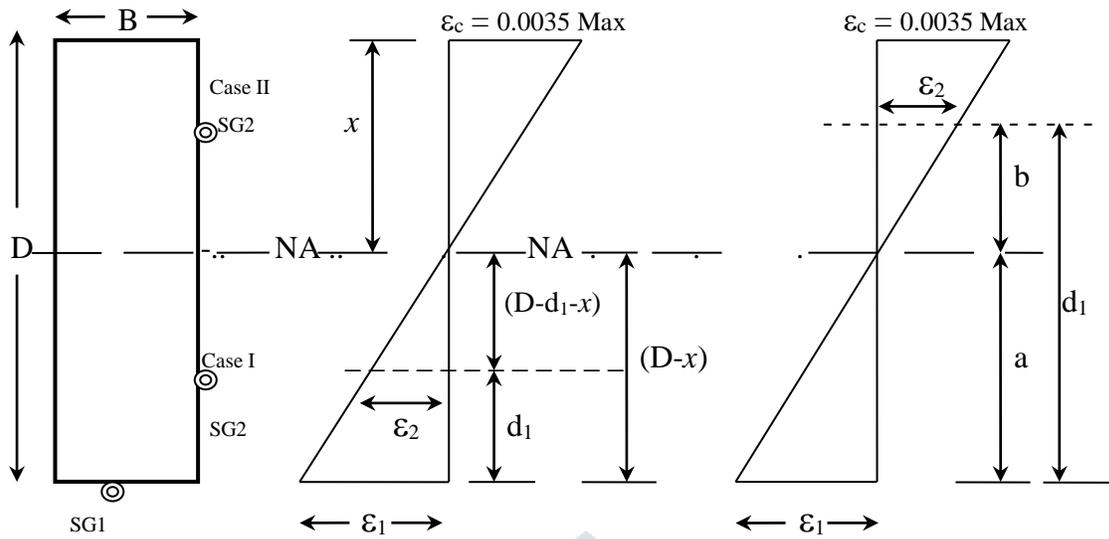


Figure 1 $\epsilon_s = [(0.87f_y/E_s) + 0.002] \text{ Max}$ $\epsilon_s = [(0.87f_y/E_s) + 0.002] \text{ Max}$
 Both Strain gauges on Tension Side Both Strain gauges on Opposite Side of NA
 Strain Diagram for Case I Strain Diagram for Case II

- Let,
- B = Width of the section,
 - D = Overall depth of the section,
 - x = Depth of Neutral axis of the section,
 - SG1 = Position of first strain gauge attached to the section,
 - SG2 = Position of second strain gauge attached to the section,
 - ϵ_1 = Strain indicated by the first strain gauge attached to the section,
 - ϵ_2 = Strain indicated by the second strain gauge attached to the section,
 - d1 = Distance of second strain gauge from bottom of the section,
 - a = Distance of neutral axis from the bottom of the section,
 - b = Distance of second strain gauge from neutral axis of the section,
 - ϵ_c = Strain in concrete.
 - ϵ_s = Strain in reinforcing steel.

9.1 Case I - Both Strain Gauges are on Tension Side

From similar triangles in strain Diagram Case I,

we can write, $\frac{\epsilon_1}{\epsilon_2} = \frac{(D-x)}{(D-d_1-x)}$

Rearranging the terms, $\frac{\epsilon_1}{\epsilon_2 + \epsilon_1} = \frac{(D-x)}{d_1}$

That gives us, $x = \left[D - \left(\frac{\epsilon_1}{\epsilon_2 - \epsilon_1} \right) d_1 \right] \dots \dots \dots (4)$

9.2 Case II - Both Strain Gauges on Opposite Side of NA

From similar triangles in strain diagram of case II,

we can write, $\frac{\epsilon_1}{a} = \frac{\epsilon_2}{b}$

Rearranging the terms, $\frac{a}{(a+b)} = \frac{\epsilon_1}{(\epsilon_1 + \epsilon_2)}$

But, from diagram it is clear that, (a+b) = d1 i.e. distance between the strain gauges, which is a known parameter.

Hence we can write the above equation as,

$$\frac{a}{d_1} = \frac{\epsilon_1}{(\epsilon_1 + \epsilon_2)}$$

$$a = \left(\frac{\epsilon_1}{\epsilon_1 + \epsilon_2} \right) d_1$$

In terms of depth of neutral axis, we can write

$$x = (D - a) = \left[D - \left(\frac{\epsilon_1}{\epsilon_1 + \epsilon_2} \right) d_1 \right] \dots \dots \dots (5)$$

The equations (4) and (5) give the depth of neutral-axis of a flexural member for different positions of strain gauges. Knowing the depth of neutral axis, we can determine whether the member is under-reinforced or balanced or over-reinforced.

10. DISCUSSION

10.1 Practical measurement of strain.

For practical measurement of strain in concrete, we have to take a help of instrument engineering branch. Now a day's various types of strain measuring gauges, instruments and data loggers are available. These instruments not only measure the required parameters but also generate a real time record of the values and store or send them to the assigned destination with assigned frequency. Thus, it is an interdisciplinary work.

10.2. LIMITATIONS FOR STRAIN MEASUREMENTS

There are some limitations in application of strain gauges that are observed as...

- 1) Strain gauges that are to be fixed on reinforcement are of very small size i.e., about 10mm x 10 mm. Generally, reinforcement steel has cover of 25 to 40 mm and it is necessary to expose the reinforcement by chipping the concrete. Also, the surface is required to be polished before sticking the strain gauge in position.
- 2) Due to their small size, it is very difficult to fix them on in-situ reinforcement. For non-wired strain gauges soldering is another on difficult job.
- 3) Small strain gauges are not suitable for concrete surfaces. Strain gauges with longer gauge length which are suitable for concrete surfaces are available in market with limited companies. To fix these 60 to 125 mm long strain gauges on the bottom of a flexural member is a difficult task.
- 4) Strain gauges need temperature-controlled soldering and a highly skilled person for soldering. Instead, it is better to use wired strain gauges.
- 5) For data generation, collection and logging in required format, some separate digital indicators and instruments are required which are costly and hence cannot be left at site.
- 6) All strain gauges are required to be fixed with epoxy adhesives and cannot be removed once fixed in position.

11. CONCLUSION

With the above method, knowing the values of strain at two different levels it is possible to find out the depth of neutral axis of the member whose reinforcement details are not known. This depth of neutral axis can be compared with that of balanced section or critical depth so as to determine whether the section is over-reinforced or under-reinforced. Subsequently with the help of other NDT, it is possible to calculate the moment of resistance of a flexural member.

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