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COMPARATIVE STRUCTURAL ANALYSIS AND REHABILITATION OF RCC BOX CULVERT USING CFRP VS. GFRP COMPOSITES: A CASE STUDY ON NH-6

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Abstract : This research focuses on the structural health assessment and subsequent rehabilitation of a reinforced concrete (RCC) box culvert (3 x 6.0m span) situated on the Odisha Border-Aurang section of NH-6. Initial inspections revealed flexural cracking, prompting a deeper investigation to determine the root causes and current structural safety. The study adopted a combined approach, utilizing theoretical design analysis alongside on-site diagnostic testing. A full-scale Bridge Load Test was executed using a 45-tonne vehicle (IRC Class A) following IRC SP-51 guidelines, supplemented by Non-Destructive Testing (NDT) methods including Ultrasonic Pulse Velocity (UPV), Rebound Hammer, and Carbonation depth analysis. While the load test indicated excellent elastic recovery (100%), surpassing the mandatory 75% limit, the structure failed serviceability requirements due to tension cracks exceeding the permissible 0.3 mm width. Based on these results, the study evaluates two retrofitting options: Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) laminates. Structural calculations indicated that while GFRP has a lower material cost, its lower modulus of elasticity necessitates 13 layers to achieve the same crack control as just 2 layers of CFRP. Therefore, CFRP was identified as the most technically and economically viable solution for this heavy-loading scenario. The proposed rehabilitation strategy involves epoxy grouting followed by the bonding of carbon fiber laminates to the deck slab.

1.Introduction

1.1 General

Aging of the structure is the critical issue globally, especially this problem is seen in various highway structure like bridges and culverts which is impacted mainly due to the increase in heavy demand of highway users. The traffic load in increasing exponentially across the globe. Reinforced concrete structures are durable in nature but it is more vulnerable to aggressive environmental effects and over usage (over loading), design inefficiency for long term traffic growth. The periodic repair and maintenance of this type of structure is very important for the safety point of view of traffic network.

For the purposes of this guideline, restoration activities are defined as follows:

- Replacement: Removal or abandonment of the existing culvert and replacing it with a new culvert pipe. This is often cost-prohibitive and causes major traffic disruption.
- Rehabilitation: Restoring the existing culvert to its initial condition or better. This is the focus of this study.
- Repair: A maintenance activity that keeps the existing culvert in a uniformly good safe condition(e.g., patching).

1.2 Problem Identification

Culvert deterioration is generally identified during scheduled inspection programs. In the case of the box culvert on NH-6 (Ch.233+515 RHS), routine inspections revealed:

1. Cracking: Pre-existing cracks at the soffit of the deck slabs and walls.
2. Distress: Signs of tensile stress exceeding the capacity of the existing reinforcement.

The specific problem identified was that while the structure could carry the load without collapsing, the crack widths under load exceeded the durability limits defined by the Indian Road Congress (IRC),posing a risk of reinforcement corrosion and long-term failure.

1.3 Strengthening Material

1. Carbon Fiber Reinforced Polymer (CFRP): Known for high tensile strength and stiffness. The original proposal included applying carbon fiber laminates to the deck slab to enhance tensile strength.
2. Glass Fiber Reinforced Polymer (GFRP): An alternative composite offering lower stiffness but higher elongation to failure and generally lower costs.
3. Comparison Objective: Determination of GFRP strengthening performance of structural rehabilitation recovery system as compared to the CFRP strengthening,

1.3.1 Carbon Fiber Reinforced Polymer (CFRP):

Carbon Fiber Reinforced Polymer (CFRP) is made of polymer resin complex matrix which is used as the high performance material (carbon fibre composite material) mainly providing reinforcing properties. The high strength less weight ratio makes it very popular engineering material to be used in construction industry. CFRP is mainly used in structural strengthening and retrofitting of complex concrete structures without adding significant extra weight to the old existing structure.

Composition:

- The "Synergy" of Two Ingredients CFRP works on the attitude of composite materials, where two different components work together to offer properties superior to any material alone.
- Material: Tremendously tinny strands of carbon molecules (5–10 microns) glued in crystals allied parallel to the fiber's axis. Function: Provides high tensile strength and stiffness (modulus).

Key Mechanical Properties:

- High Strength-to-Weight Ratio: CFRP is approximately 5 times stronger than steel but weighs only about 20% as much.
- Corrosion Resistance: Unlike steel, carbon fiber does not rust. This makes it ideal for harsh environments (e.g., bridges over saltwater, chemical plants).
- High Modulus of Elasticity: It is incredibly stiff, minimizing deformation under load.
- Fatigue Resistance: It withstands cyclic loading (repeated stress) much better than steel or aluminum.
- Anisotropy: CFRP is "anisotropic," meaning its strength is directional. It is incredibly strong along the direction of the fibers but weaker across them.

Applications in Retrofitting:CFRP is primarily used to restore or increase the load-bearing capacity of existing structures (Retrofitting).

- Flexural Strengthening (Beams & Slabs): A beam needs to carry more load than originally designed (e.g., change in building use). CFRP laminate strips are bonded to the bottom (tension face) of the concrete beam. The CFRP acts like external reinforcement bars, taking the tension load.
- Shear Strengthening (Beams): A beam shows diagonal cracks near supports (shear failure). CFRP sheets are wrapped around the sides and bottom of the beam (U-wrap) to act as external stirrups.
- Confinement (Columns): A column is weak in compression or lacks ductility (seismic risk).The column is fully wrapped in CFRP sheets. As the column tries to expand outwards under vertical load (Poisson's effect), the CFRP "jacket" restrains it. This confinement significantly increases the concrete's compressive strength and ductility.

Note: Circular columns benefit most from this. Square columns often require their sharp corners to be rounded off before wrapping to prevent the fiber from snapping at the edge.

1.3.2 Glass Fiber Reinforced Polymer (GFRP):

Glass Fiber Reinforced Polymer (GFRP) is a composite material made of a polymer matrix reinforced with glass fibers. While similar in concept to Carbon Fiber (CFRP), GFRP is distinct because it is significantly more affordable and widely used as a direct replacement for steel rebar in corrosive environments. In civil engineering, it is often referred to as "fiberglass rebar.".

Composition:

- Just like CFRP, GFRP relies on two main components, but the materials differ to optimize for cost and specific environmental resistance. The Reinforcement (Glass Fibers) Usually E-Glass (Electrical grade) or CR-Glass (Corrosion Resistant). Which Provides the tensile strength. Glass fibers have high strength but are less stiff (lower modulus) than carbon or steel.
- The Matrix (Polymer Resin): Typically Vinyl Ester or Polyester resin. Vinyl ester is preferred in construction because it offers superior resistance to alkali attacks (the high pH found naturally in concrete) compared to cheaper polyester.

Key Mechanical Properties:

- Electromagnetic Neutrality: Unlike steel, GFRP is non-magnetic and non-conductive. It is "transparent" to radio waves and magnetic fields.
- Corrosion Immunity: It creates a rust-free infrastructure. It is impervious to chloride ions (from ocean water or de-icing salts) and aggressive chemicals.
- Low Modulus of Elasticity: This is its main structural limitation. GFRP is "stretchy" compared to steel. Steel Modulus: ~200 GPa, GFRP Modulus: ~40–60 GPa,
- Implication: You often need more GFRP bars than steel bars to control cracks and deflection, even if the GFRP is stronger in tension.
- Thermal Insulation: It does not conduct heat, preventing thermal bridging in building envelopes.

Applications in Retrofitting*:*

Soft-Eye in Tunnelling (TBMs): A Tunnel Boring Machine (TBM) needs to drill through a concrete retaining wall (the launch or reception shaft) to start or finish a tunnel. Engineers reinforce the area of the wall where the TBM will pass (the "eye") with GFRP instead of steel. The TBM's cutter head can easily chew through glass fiber bars. If the wall were reinforced with steel, the steel would damage the expensive cutter head.

- MRI Rooms & Sensitive Electronics: Hospitals require Magnetic Resonance Imaging (MRI) rooms, which use massive magnets. Steel rebar in the floor or walls can interfere with the MRI's magnetic field, causing "ghosting" in images. GFRP is used for the concrete slabs in these rooms because it is magnetically transparent.
- Marine & Coastal Structures: Seawalls, jetties, and bridge decks exposed to salt spray. Steel rebar expands when it rusts, causing concrete to spall (break off). GFRP eliminates this "concrete cancer," significantly extending the lifespan of marine structures.

1.4 Bridge Investigation

1.4.1 Identify the Root Cause

Culvert deterioration is generally identified and monitored during a scheduled inspection programme of highway roads and structures. Other sources of identified culvert deterioration come from roadway project designers, or notifications from maintenance staff who observe roadway settlement, sinkholes or ponding water at the inlet structure.

The overall culvert condition is inspected and maintained a database by the scheduled inspection and maintenance team. The culvert's overall condition is rated on a scale from 0 to 4, listed below.

0. Not able to rate, not visible
1. Excellent – like new condition
2. Fair – some wear, but structurally sound
3. Poor – deteriorated, consider for repair or replacement
4. Very Poor – serious condition

The overall culvert condition and recommended inspection frequency is given in table below:

Overall Condition	Recommended Inspection Frequency (Years)	Comments
4 Very Poor		
3 Poor		
1 & 2 Like New and Fair		
0 Can't Be Rated		

It is strongly recommended that culverts with an overall condition rating of 3 or 4 receive some level of repair, rehabilitation or replacement. The timing will be influenced by the location of the deterioration and the potential for increased damage to the pipe and roadway above. Determining the level of deterioration the culvert has sustained is an important part of deciding to repair, rehabilitate or replace it. Routinely monitoring the deterioration will assist in determining when repairs should be made, before rehabilitation or replacement is required.

1.4.2 Determine the Causes of Deterioration

Understanding the cause of deterioration is the key to developing a plan to replace, rehabilitate or repair a culvert. Every effort should be made to reduce or eliminate the source of deterioration, either by modifying the original design or selecting an alternative material that is less susceptible to the source of deterioration. Information from the scheduled inspection database will also assist in determining the cause. Establishing the rate and location of deterioration is also a key factor in determining the cause.These observations can be used to assist in the plan to rehabilitate, repair, or replace the culvert and in selecting alternative materials. Consideration should be given to what other negative factors can be engineered out of a new installation to increase longevity of the new culvert.

1.4.3 Evaluate Structural Condition

Determining the structural capacity of a deteriorated culvert is not a simple and straightforward task. The residual structural capacity and resulting factor of safety is influenced by a number of factors such as culvert pipe material properties, quality of pipe installation and loading. There are numerous cases where a culvert remains generally stable when the condition indicates it should have failed. The reverse is also true, when culverts have excessive deformation or deterioration for no apparent reason. Examples of factors that may increase the residual structural capacity of deteriorated culverts include: The RCP culvert pipe yield and compressive strength of reinforcement and concrete exceeded minimum design values, resulting in additional capacity, The loss or reduction of soil support due to piping, or soil infiltrating through pipe joints, tears or holes, The excessive deformation (> 10% deflection) of flexible culverts or reverse curvature of shape, leading to pipe buckling and collapse, Exposure and loss of reinforcement section in the invert of RCP culverts resulting loss of bending moment capacity.

The non destructive and destructive tests techniques were used to determine the structural stability is as follows:

Destructive test:

- Core cutter test
- Carbonation test
- XRD and Sem test to determine the structural integrity of concrete structures

Non-destructive testing's:

- Rebound hammer test
- UPV test

- Bridge load test
- Crack depth measurement test

1.4.4 Scope of Comparative Study:

This research analyzes the load test data from the BSCPL Aurang Tollways project to design strengthening systems using both Carbon and Glass fibers, evaluating them on stiffness, application thickness, and cost.

1.5 Objective of the study

The main objective is to check the structural stability and concrete integrity of the box culvert and provide a suitable and viable rehabilitation solution accordingly. The detailed objectives of the study are as follows:

1. To determine the structure integrity of box culvert by using Non-Destructive Tests (NDT) and Destructive Tests (Core Cutting).
2. To evaluate the structural recovery of box culvert by full scale bridge load test
3. To evaluate the best suitable structural strengthening system with respect to the comparative study (design and economy) of CFRP and GFRP systems.
4. Provide the detailed structural rehabilitation methodology for the above mentioned box culvert.

2.0 Literature Review

The rehabilitation and strengthening of reinforced concrete structures(RCC), mainly highway bridges and culverts, need a profound thoughtful of structural health monitoring (SHM), non-destructive testing (NDT), and knowledge of advanced composite materials and there design and applications. In this chapter we discuss the relevant literatures and reference standards used for the above-mentioned subject.

2.1 Structural Health Monitoring and Load Testing

1. IRC:SP-51 (2015), "Guidelines for Load Testing of Bridges": This code offers the standard outlines for evaluating the performance of various type of bridges and culverts in India. The above mentioned standard specify that the RCC structures have deflection recovery of at least 75% in 24 hours after load removal shows elastic behaviour of the structure. This standard also summaries the criteria for crack width limitations and failure pattern of the concrete which is primary objective of this study.
2. Faber, M. H., et al. (2000), "Assessment of Existing Structures": Authors discusses the reliability-based assessment of existing highway bridges. The study highlights that hypothetical capacity repeatedly underestimates actual performance due to composite action and material over-strength. However, it emphasizes that serviceability limits (deflection/cracking) are often the governing factors for older structures, aligning with the findings of the NH-6 culvert.
3. Bakht, B. and Jaeger, L.G. (1990), "Bridge Testing - A Surprise Every Time": The above research article explain about the static load testing behaviour which reveals the "true" behavior of a bridge, which often differs from the "design" behavior. The authors recommend analytical load testing as a compulsory step before decisive on rehabilitation versus replacement.

2.2 Non-Destructive Testing (NDT) of Concrete

1. IS:13311 (Part 1 & 2), "Non-Destructive Testing of Concrete": Part 1 covers the Ultrasonic Pulse Velocity (UPV) method, establishing velocity criteria (>4.5 km/s for excellent concrete). Part 2 covers the Rebound Hammer test. These standards were instrumental in assessing the homogeneity of the culvert concrete in this study.
2. Bungey, J. H. (1989), "Testing of Concrete in Structures": Bungey provides a comprehensive review of NDT methods. The author notes that while Rebound Hammer is useful for surface hardness, it must be correlated with core tests for accuracy. This methodology was adopted in this study by supplementing NDT with core cutting.
3. Malhotra, V. M. (1976), "Testing Hardened Concrete: Non-destructive Methods"

Malhotra's work validates the use of UPV for detecting internal voids and honeycomb areas. The study concludes that UPV is the most reliable method for assessing the quality of grouting post-repair, a technique proposed in the rehabilitation plan of this thesis.

2.3 Fiber Reinforced Polymers (FRP) in Strengthening

1. ACI 440.2R-17, "Guide for the Design and Construction of Externally Bonded FRP Systems": This ACI guide is the global standard for FRP design. It provides the design equations for flexural strengthening, shear strengthening, and confinement. The guide introduces the environmental reduction factors (C_E) used to account for long-term degradation, which were considered in the design philosophy of this thesis.
2. Teng, J. G., et al. (2002), "FRP Strengthened RC Structures": Teng provides a detailed analysis of failure modes in FRP-strengthened beams, specifically debonding (peeling off) at the plate ends. The book recommends using U-wraps or mechanical anchors at the ends of laminates to prevent premature failure, a detail incorporated into the methodology for the NH-6 culvert.
3. Meier, U. (1987), "Carbon Fiber-Reinforced Polymers: Modern Materials in Bridge Engineering": One of the earliest papers on the subject, Meier compares steel plate bonding with CFRP. The study demonstrates that while steel plates are cheaper, they are heavy and prone to corrosion. CFRP, being lightweight and corrosion-resistant, offers lower installation costs despite higher material costs.

2.4 Comparative Studies: CFRP vs. GFRP

1. Grace, N. F., et al. (1998), "Ductility of FRP Strengthened Bridges": This comparative study tested beams strengthened with CFRP and GFRP. The study evaluated ductility and stiffness. Beams strengthened with CFRP showed significantly higher stiffness and lower crack widths compared to GFRP. However, GFRP beams exhibited more ductility (warning before failure). Supports the finding of this thesis that CFRP is superior for stiffness-driven designs (crack control).
2. Karbhari, V. M. and Zhao, L. (2000), "Use of Composite Wrap Systems for Rehabilitation": Comparing Carbon, Glass, and Aramid fibers. Carbon fiber had the best durability in alkaline environments (concrete) and the highest stiffness-to-weight ratio. Glass fiber showed degradation over time in moist concrete environments. Carbon is recommended for critical infrastructure where long-term durability is paramount.
3. Al-Amery, R. and Al-Mahaidi, R. (2006), "Coupled Flexural-Shear Retrofitting of RC Beams using CFRP": Experimental testing of CFRP laminates. CFRP provided a 40-60% increase in ultimate load capacity. Validates the capacity increase assumed in the design calculations.
4. Shahawy, M. A., et al. (1996), "Flexural Behavior of Concrete Beams Strengthened with CFRP": This study confirmed that the number of CFRP layers is directly proportional to the stiffness increase, but beyond a certain thickness, the failure mode shifts from concrete crushing to delamination. This supports the decision in this thesis to limit CFRP to 2 layers rather than using thick GFRP plates (10+ layers).
5. Saadatmanesh, H. and Ehsani, M. R. (1991), "RC Beams Strengthened with GFRP Plates": Investigated GFRP for flexural strengthening. While GFRP increased strength, significant cracking was observed at service loads due to the low modulus of elasticity of Glass fibers. GFRP is less effective than CFRP for crack width control.

2.5 Summary of Literature

The summary of the above literature and standards reviews key points are listed below:

- Load Testing: The most reliable testing method as per IRC SP 51 is static load testing of bridges.
- Stiffness vs. Strength: The stiffness properties of the materials are more important for serviceability of the structure than the ultimate strength of the materials.
- Material Selection: many researches highlights the significant superiority of CFRP strengthening material over GFRP material as there applications demands high stiffness and durability, despite the higher unit cost.
- Application: Multiple layers of CFRP increase the risk of delamination; therefore, thinner, high-stiffness laminates (CFRP) are preferred over thick, low-stiffness laminates (GFRP).

3.0 Methodology

3.1 General

In this chapter brief methodology is explain for the bridge load test and various non-destructive testing's. The detailed procedure and testing programs were explained and letter on the findings and recommendations were listed. The repair methodology with detailed application procedure were explained followed by post testing plans.

3.2 Bridge Load Testing (as per IRC SP 051: Guideline for bridge load test):

IRC SP 51: Guidelines for the bridge load provides the detailed procedure to perform the bridge load test and calculate the load recovery of the bridge. It also explain the acceptance criteria and performance evaluation of the bridge.

3.2.2 Flow Chart of Activities

The Bridge load test requires the pre-test arrangements of vehicle and preplanning of sequence of events; hence it is necessary to plan your activities accordingly. The detailed step by step activities are listed below:

a. Primary site visit to plan the whole 2 days activities and manage the traffic at testing time.
b. Whitewash of the bottom of the critical member (deck slab).
c. Visual inspection of whole bridge.
d. Check and note down the existing status of the bridge.
e. Setting out of defection recording instruments (dial gauge)
f. Record the initial temperature using thermometer and install the thermometer adjacent to dial gauge to record temperature simultaneously(for temperature correction its necessary).
g. Place the vehicle above the deck slab to apply the load as per the plan.
h. Start measuring the deflection and temperature as per said procedure in IRC SP 51.
i. Removal of load as per plan and record the recovery time and rate of recovery for 24 hours.
j. Preparation of detailed report as per the observations.

A flow chart shall be prepared for the above said activities as also any other additionally

3.2.3 Types of Load Tests: Static load tests are most continent and suitable methos recommended by the IRC SP51. Hence the Static vehicular loading pattern is adopted in this test.

3.2.4 Details of the Box Culvert Bridge:

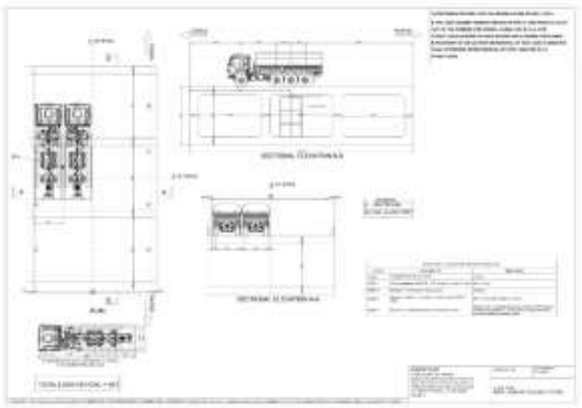
In this study Load Testing of a high RCC minor box type bridge deck on(3x6.0x4.0 m)(old Existing Bridge) at Ch.233+515 RHS for "Four Lanning of Orissa Border - Aurang Section from km 88/000 to km 239/000 of NH-6 in the State of Chhattisgarh to be executed as BOT (Toll) on DBFOT Pattern under NHDP Phase IV" as per IRC SP-37 2010 and IRC SP-51 2015. The bridge was constructed by CG State department. However, the bridge is now-a-days being used by NHAI where this bridge experiences heavy traffic. Because of heavy traffic, only one span of the bridge was randomly tested by assuming that the other spans would exhibit a similar load-deflection trend. In order to assess the stability of the deck under full load, load test has been performed under the supervision of VNIT Nagpur team and the results are then furnished from the VNIT Nagpur team for this study.

3.2.5 Methodology of Load Test:

- Bottom of superstructure is to be inspected. Any pre-existing cracks observed are to be clearly marked and crack width recorded.
- Before the loading arrangement, deflectometers shall be fixed at mid span and two quarter spans below the box girder below the loading region. The initial readings shall be noted and the loading is positioned
- The loading was applied as per IRC specifications for class A loading. Static loading was simulated with the help of two test trucks (Crushed stone) each weighing approximately 45 tonnes.
- The trucks were aligned in such a manner so as to cause maximum sagging bending moment in the deck slab, the detailed drawing is attached for your reference.
- After affixing three dial gauges (one each at the bottom of the slab just below the wheels of vehicle and one at the centre of the slab) and taking the initial readings, test load through trucks was applied in two phases as explained ahead.
- The first reading was taken by placing only one truck (50% design load) at the designated location and Readings were taken 5 minutes after placing the static load. The first truck weighed 45 tonnes.

- The second reading was taken by placing both trucks (100% design load) at the designated location. Second truck weighed 45 tonnes.
- The deck is checked for the presence and widening of flexural cracks, if any, at every step of loading. The load is maintained for 24 hours on the deck. After 24 hours, the final readings are to be noted and deck checked for cracks, if any.
- Then the loading is removed. Unloading should also be done in same percentage as that of loading. On removal of each load decrement, the deflectometers readings are to be noted. The percentage recovery of deflection is calculated after 24 hours of removal of static load.
- The gauge readings were noted down after every hour until a constant reading is observed on the dial gauges. This reading is used to calculate the final recovery.

Schematic drawing of loading arrangement of vehicle of four lanning road at aurang section of NH6 In the State of Chhattisgarh.



3.2.6 Acceptance Criteria: Requirements for deflection criteria, tension crack width criteria, diagonal crack width criteria and percentage recovery criteria is given in Cl. 8.6.2, IRC SP-37 2010 and we follow this recommendation strictly.
3.2.7 Test Results: The calculation of percentage recovery is done as given in IRC SP51 after applying temperature and / or rotation correction to deflection date.

3.2.8 Preparatory work:

- All visual defects seen shall measure, recorded and plotted before start of testing.
- Check the positioning and placement of recording dial gauges and devices are firmly placed.
- Loading vehicle is to be checked twice before start of test to avoid the disturbance on between the test period

3.2.9 Procedure for Temperature Correction: - A digital calibrated thermometer is placed for monitoring temperature of the bridge deck. The probe could be inserted in a perforated hole in the concrete surface, for recording temperature.

3.3 Non-Destructive Testing Methodology:

3.3.1 Rebound Hammer Test:

The most satisfactory way of establishing a correlation between compressive strength of concrete and its rebound number is to measure both the properties simultaneously on concrete cubes. The concrete cube specimens are held in a compression testing machine under a fixed load, measurements of rebound number taken and then the compressive strength determined as per IS-516 (Part 5/Sec 4): 2020 "Non-Destructive Testing of Concrete Section 4 Rebound Hammer Test". The fixed load required is of the order of 7 N/mm2 when the impact energy of the hammer is about 2.2 Nm. The load should be increased for calibrating rebound hammers of greater impact energy and decreased for calibrating rebound hammers of lesser impact energy. The test specimens should be as large a mass as possible to minimize the size effect on the test result of a full-scale structure. 150 mm cube specimens are preferred for calibrating rebound hammers of lower impact energy (2.2 Nm), whereas for rebound hammers of higher impact energy, for example 30 Nm, the test cubes should not be smaller than 300 mm. If the specimens are wet cured, they should be removed from wet storage and kept in the laboratory atmosphere for about 24 hours before testing. To obtain a correlation between rebound numbers and strength of wet cured and wet tested cubes, it is necessary to establish a correlation between the strength of wet tested cubes and the strength of dry tested cubes on which rebound readings are taken. A direct correlation between rebound numbers on wet cubes and the strength of wet cubes is not recommended. Only the vertical faces of the cube as cast should be tested. At least nine readings should be taken on each of the two vertical faces accessible in the compression testing machine when using the rebound hammers. The points of impact on the specimen must not be nearer an edge than 20 mm and should be not less than 20 mm from each other. The same points must not be impacted more than once.

Reference: IS-516 (Part 5/Sec 4): 2020 “Non-Destructive Testing of Concrete Section 4 Rebound Hammer Test”.

Calibration and equipment used: It is necessary that the rebound hammer is checked against the testing anvil before commencement of a test to ensure reliable results.

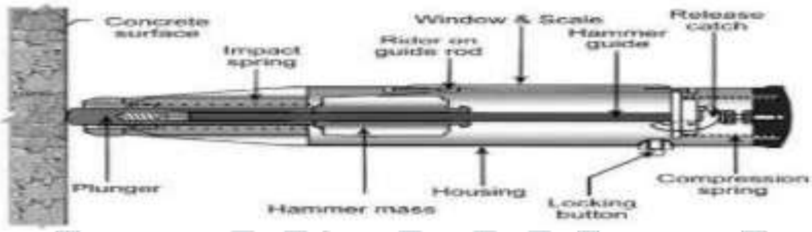
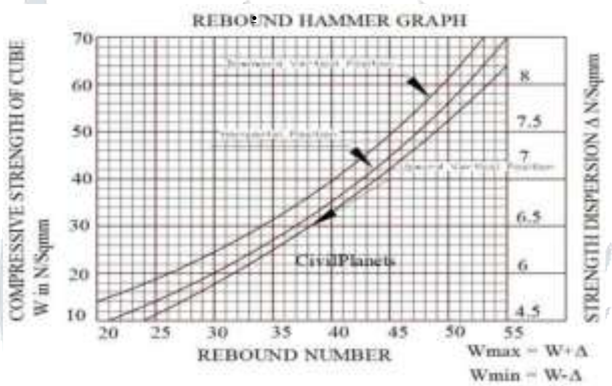


Figure 3.3.1 Rebound Hammer Equipment



RESULTS: - Details of the results are mentioned in Annexure-1 along with the Graph

3.3.2 Ultrasonic Pulse Velocity (UPV) Test:

Ultrasonic Pulse Velocity (UPV) Test is used to measure the concrete integrity and homogeneity of concrete. This non destructive testing technique is mainly based on the velocity of pulse velocity transmitted through the concrete. It measure the time taken to transmitted pulse from the transmitter probe to receiver probe. The Velocity of concrete mainly depends upon the concrete density, uniformity, voids and cracks if presents inside concrete. The quality of concrete is measured in relation to the specified standard requirements given in IS 516-2019, (Part 5, Section 1) Non-destructive testing of concrete - Methods of test: Ultra-Sonic Pulse Velocity. The acceptance criteria are explained in image 3.3 taken from the mentioned Indian standard. There are two methods of testing surface probing and direct transmission, the detailed procedure is explained in IS 516 part5 section1.

Reference: S: 516-2019, (Part 5, Section 1) Non-destructive testing of concrete - Methods of test: Ultra-Sonic Pulse Velocity. The acceptance criteria are explained in image 3.3.

Figure:3.2: UPV Test Instrument

Table 1 Velocity Criteria for Concrete Quality Grading

(*Clause* 2.5.2)

Sl No. (1)	Average Value of Pulse Velocity by Cross Probing km/s (2)	Concrete Quality Grading (3)
i) For concrete (≤ M 25):		
a)	Below 3.5	Doubtful[1)]
b)	3.5 – 4.5	Good
c)	Above 4.5	Excellent
ii) For concrete (> M 25):		
a)	Below 3.75	Doubtful[1)]
b)	3.75 – 4.50	Good
c)	Above 4.50	Excellent

[1)] In case of 'Doubtful quality', it shall be necessary to carry out additional tests.

Figure: 3.3: Acceptance criteria as per IS 516-2019, (Part 5, Section 1)

3.3.3 Carbonation Test:

The carbonation test is done as per IS-516 (Part 5/Sec 3):2021, carbonation test is a method to measure the depth of carbonation in hardened concrete. This test is crucial for assessing the durability of concrete structures, as carbonation is responsible for the corrosion of embedded reinforcement, ultimately compromising the structural integrity of the concrete.

Reference: IS-516(Part 5/Sec 3):2021 "Non-Destructive Testing of Concrete- Section 3 Carbonation Depth Test"

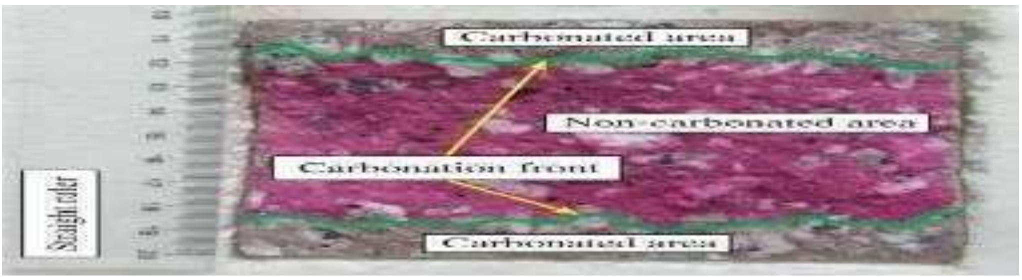


Figure. 3.4: Carbonation Depth Test

3.4 Non-Destructive Test (concrete core compressive strength test) Methodology:

Objective: The objective of core cutter test is following:

- Visually inspect the interior of the concrete.
- Compressive strength of concrete with laboratory testing
- Chemical testing for determining density of concrete, water absorption capacity, split(indirect) tensile strength of concrete core, and expansion due to alkali-aggregate reaction etc.

- After compressive strength testing, test samples can further be used for chemical analysis for concluding on ratio of concrete mix components (Cement: Sand: Aggregates) .

Principle: Core cutting and testing is a process commonly used in industries such as geology, mining, and materials science to analyze the internal structure and properties of materials, particularly rocks and other solid substances. The principle involves extracting cylindrical samples, or "cores," from a larger material or geological formation, and then subjecting these cores to various tests and analyses to determine their physical and mechanical properties.

Reference: The testing of concrete cores is carried out according to IS 516 (Part 4):2018.

Field Sample Collection: A HILTY Core drill machine (shown in the figure below) is used for taking out core from the specified location. Minimum of three core samples are taken from different locations. From locations, where core of concrete is withdrawn for testing, shall be duly refilled with concrete.

Sample Preparation for testing:

- The concrete cores are smooth at both ends using high quality concrete cutting machine shown in Figure 5.3.2 By using this machine, we can easily get a smooth surface within the flatness tolerance limit ± 0.05 mm as specified in Cl. 7.5 of IS 516(Part 4):2018. Vernier Calipers and scale was used for measuring the dimensions and flatness tolerance specified in Cl. 7.6 of IS 516 (Part 4):2018 and shown in Figure 5.3.3.

Figure 3.5: Hilti Core Drill machine

- Then these prepared samples are soaked in water at 27 ± 3°C for a at least of 40 hour.
- After soaking in water for 40 hours the core samples were removed and remove all excess water and kept outside for 1 hour to get dried before testing for compressive strength of samples.
- As concrete core surface was prepared by proper grading and ensured that load is applied evenly as the flatness of the sample was under the tolerance limit as shown in Figure 5.3.3. Therefore, no capping was needed to apply [as per Cl. No.7.1 from IS 516 (Part 4) 2018]:
- The compressive strength of the core samples are determined using compression testing machine. And the equivalent compressive strength of concrete cores were calculated as per the relevant Indian standard IS 516 part 4: 2018.

Figure 3.6: High quality concrete cutting machine

4 RESULTS AND DATA ANALYSIS

4.1Bridge Load Test Results:

4.1.1 Temperature Observation:

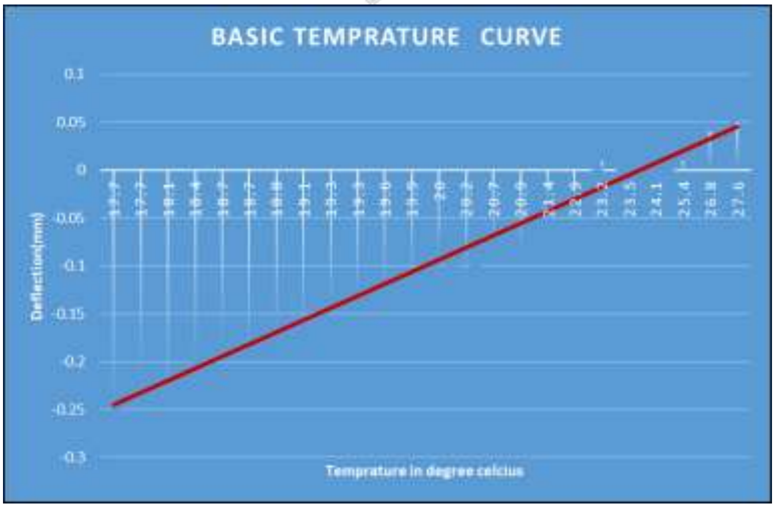
Table 4.1.1: Temperature observation

After	Time HH:MM	Temp ©	Deflection readings centre of slab	Remark
0 Hr	15:00	24.1	5.29	
1 Hr	16:00	23.5	5.29	
2 Hr	17:00	23.2	5.3	
3 Hr	18:00	21.4	5.26	
4 Hr	19:00	20.7	5.22	
5 Hr	20:00	20	5.2	

6 Hr	21:00	19.6	5.17	
7 Hr	22:00	19.3	5.15	
8 Hr	23:00	19.1	5.13	
9 Hr	00:00	18.7	5.11	
10 Hr	01:00	18.7	5.1	
11 Hr	02:00	18.4	5.09	
12 Hr	03:00	18.1	5.05	
13 Hr	04:00	17.7	5.04	
14 Hr	05:00	17.7	5.08	
15 Hr	06:00	18.8	5.12	
16 Hr	07:00	19.3	5.16	
17 Hr	08:00	19.9	5.18	
18 Hr	09:00	20.2	5.18	
19 Hr	10:00	20.9	5.21	
20 Hr	11:00	22.9	5.26	
21 Hr	12:00	27.6	5.34	
22 Hr	13:00	26.8	5.33	
23 Hr	14:00	25.8	5.3	

Note: During the temperature correction, temperature ranges from 17.7 to 32.0 degree Celsius. The temperature deflection characteristics was taken from the graph below which is the linear line drawn between points of minimum temperature- least deflection and maximum temperature- most deflection.

Figure 4.1.1: Dial gauge arrangements



4.1.1 Deflection and Recovery data

Table 4.1.2: Deflection and Recovery data

Readings for Thermometer and Dial Gauges during 24 hrs Retention Period								
% Load After	**Date**	**Time (HH:MM)**	**Temp**	**Gauge Readings (in mm)**				
				#1	**#2**	**#3**	**#4**	**#5**
0%	23-06-2025	14:15	25.40	5.16	5.00	5.00	4.64	6.00
50%	23-06-2025	14:30	25.30	5.37	5.04	5.07	4.65	6.00
100%	23-06-2025	15:30	23.90	5.37	5.16	5.13	4.78	6.19
1 Hr	23-06-2025	16:30	23.40	5.18	5.15	5.13	4.78	6.18
2 Hr	23-06-2025	17:30	23.10	5.15	5.14	5.09	4.76	6.10
3 Hr	23-06-2025	18:30	21.30	5.13	5.10	5.07	4.70	6.08
4 Hr	23-06-2025	19:30	20.50	5.10	5.05	5.00	4.68	6.03
5 Hr	23-06-2025	20:30	20.20	5.10	5.00	5.00	4.62	5.98
6 Hr	23-06-2025	21:30	19.50	5.06	4.99	4.98	4.60	5.95
7 Hr	23-06-2025	22:30	19.20	5.06	4.97	4.98	4.59	5.93
8 Hr	23-06-2025	23:30	19.40	5.06	4.96	4.98	4.59	5.93
9 Hr	24-06-2025	00:30	18.80	5.06	4.96	4.98	4.59	5.93
10 Hr	24-06-2025	01:30	18.90	5.06	4.96	4.98	4.59	5.93
11 Hr	24-06-2025	02:30	18.20	5.06	4.96	4.98	4.59	5.94
12 Hr	24-06-2025	03:30	18.00	5.06	4.96	4.98	4.59	5.93
13 Hr	24-06-2025	04:30	17.80	5.06	4.96	4.98	4.59	5.93
14 Hr	24-06-2025	05:30	17.90	5.06	4.96	4.98	4.59	5.94
15 Hr	24-06-2025	06:30	17.80	5.10	5.00	4.99	4.63	5.97
16 Hr	24-06-2025	07:30	18.90	5.15	5.05	4.99	4.67	5.99
17 Hr	24-06-2025	08:30	19.60	5.23	5.05	5.00	4.68	6.05
18 Hr	24-06-2025	09:30	20.00	5.30	5.07	5.03	4.70	6.11
19 Hr	24-06-2025	10:30	20.50	5.36	5.10	5.05	4.73	6.15
20 Hr	24-06-2025	11:30	22.40	5.36	5.11	5.07	4.75	6.15
21 Hr	24-06-2025	12:30	23.40	5.37	5.13	5.07	4.76	6.18
22 Hr	24-06-2025	13:30	25.60	5.37	5.16	5.09	4.78	6.18
23 Hr	24-06-2025	14:30	26.50	5.36	5.16	5.11	4.78	6.19
24 Hr	24-06-2025	15:30	26.60	5.37	5.16	5.12	4.78	6.19
	Max. deflection for constant gauge readings (in mm)			**5.37**	**5.16**	**5.13**	**4.78**	**6.19**
After Removal of load	24-06-2025	0.67	25.20	5.16	5.00	5.00	4.64	6.00

Table 4.1.3: Temperature Correction

Temperature Correction	Temperature (0C)	Correction (mm)
Deflections observed from basic Temperature curve for the required temperatures for temperature correction	24.7	0.00
	25.4	0.03
	26.6	0.04
	25.2	0.02
	23.2	-0.01

Table 4.1.4: Recovery of Deflection Calculation

Recovery of deflection calculations after Temperature Correction							
Description	Notation	Temp. (^{0}C)	Corrected Dial Gauge Readings (in mm)				
			#1	#2	#3	#4	#5
Initial Values-Deflection before application of loading	R1	24.7	5.16	5.00	5.00	4.64	6.00
Deflection after 1 hour, after applying 100% test load	R2	25.4	5.40	5.19	5.16	4.81	6.19
Deflection after 24 hour retention of 100% test load	R3	26.6	5.33	5.20	5.16	4.82	6.23
Deflection immediately after removal of test load	R4	25.2	5.16	4.98	5.00	4.60	5.98
Final Recovery after removal of test load	R5	23.2	5.16	5.00	5.00	4.64	6.00
Total Deflection	R3-R1		0.17	0.2	0.16	0.18	0.23
Total recovery of deflection after 24 hour after removal of test load	R3-R5		0.17	0.20	0.16	0.18	0.23
Percentage of recovery of deflection at 24 hour after removal of test load	[(R3-R5)/(R3-R1)] X100		100.00	100.00	100.00	100.00	100.00
Target Recovery (75% for RCC) (Cl. 6.8.2, IRC SP-51 2015)			75%	75%	75%	75%	75%
Remarks			SAFE	SAFE	SAFE	SAFE	SAFE

4.1.3 Acceptance Criteria Analysis:

Table 4.1.5: Acceptance Criteria as per IRC SP-37:2010

Requirements as per Cl. 8.6.2, IRC SP-37 2010	Remarks
The load causing a deflection of 1/1500 of the span in any of the main girders for simply supported spans in any of the main girders. The rotation of pier should be accounted for while calculating the deflection.	Maximum deflection is 0.21 mm which is less than the permissible maximum deflection limit of 8.723mm (for 3 cell box type bridge having Span=6m) Hence, OK.

The load causing tension cracks of width more than 0.3mm in any of the girders for normal conditions.	Tension crack is observed more than 0.3 mm width at the slab, Hence unsatisfactory.
The load causing appearance of visible new diagonal cracks of width more than 0.3mm for normal conditions or opening/widening of existing cracks close to the supports in concrete girders	No new diagonal cracks were observed. Hence, OK.
The load at which recovery of deflection on removal of test load is not less than 75% for RCC structures	Deflection recovery was more than 75%. Hence, OK.

Discussion: While the bridge is elastically sound (it bounces back), the excessive crack width indicates a lack of stiffness in the tension zone. This requires external strengthening.

4.2 Non-Destructive test results

4.2.1 Rebound Hammer Test Results:

Rebound hammer test where values are taken by making a grid pattern of 500*500mm. and the average values are tabulated below.

Table 4.2.1: Summary of Rebound Hammer test Results

Sl. No.	Member	Average Rebound Hammer Value	Observation
1	Abutment Wall -1	35	Vertical Cracks were Observed
2	Wall-1	35	
3	Wall-2	34	Vertical Cracks were Observed
4	Wall-3	39	Vertical Cracks were Observed
5	Wall-4	39	Vertical Cracks were Observed
6	Wall-5	35	Vertical Cracks were Observed
7	Wall-6	35	-
8	Abutment wall -2	34	-
9	Slab-1	37	Crack Width is more than 0.3 mm
10	Slab-2	41	Small cracks were observed
11	Slab-3	39	Small cracks were observed
12	Slab-4	40	Small cracks were observed
13	Slab-5	38	-
14	Slab-6	39	-

Summary: The Rebound Hammer test was conducted on 14 structural members (walls and slabs) to assess surface hardness and estimate compressive strength. The average rebound hammer values observed in the range of 34 to 41. Lowest values were observed is 34 in Wall-2, Abutment Wall-2 and Highest value observed is 41 in Slab-2. As per relevant Indian standard the above values indicate the good hardness probable to a medium-strength grade of concrete (approx. M20–M30, subject to calibration).
Visual Observations: The vertical cracks were observed mostly in all walls. Crack width exceeding 0.3mm is observed in the slab 1 only and some irrelevant small cracks were also observed in other slabs. The distress were seen in both slab and wall of the box culvert.

4.2.2 UPV Test Results:

UPV values are taken by making a grid pattern of 500*500mm. and the average values are tabulated below.

Table 4.2.2: Summary of UPV test Results

Sl. No.	Member	Average UPV values in m/s
1	Abutment Wall -1	3750
2	Wall-1	3794

3	Wall-2	4193
4	Wall-3	4105
5	Wall-4	4138
6	Wall-5	4138
7	Wall-6	3867
8	Abutment wall -2	3952
9	Slab-1	3769
10	Slab-2	4106
11	Slab-3	3616
12	Slab-4	4116
13	Slab-5	4760
14	Slab-6	3741

Summary: UPV testing was conducted to assess the homogeneity and quality of the concrete. The pulse velocities ranged between 3616 m/s and 4760 m/s. Quality Classification (based on IS516 Part5:section 1): Excellent (> 4500 m/s): Observed in Slab-5 (4760 m/s). Good (3500 – 4500 m/s): All other 13 members fall into this category. The UPV results suggest that the internal integrity of the concrete is "Good" to "Excellent," with no members falling into the "Medium" or "Doubtful" categories.

4.2.3 Carbonation Test Results:

Table 4.2.3: Summary of Carbonation test Results

ID. NO	Verified as per IS Code	Observed Results	Remarks
P5 SIDE WALL	IS-516 (Part 5/Sec 3):2021	Light Pink	Carbonation has started, increasing risk of corrosion
P5/RHS/233+515/MNB/3		Light Pink	Carbonation has started, increasing risk of corrosion
P4/RHS/253+515/2		Light Pink	Carbonation has started, increasing risk of corrosion
P2 wall		Light Pink	Carbonation has started, increasing risk of corrosion,
P4/RHS/253+515/1		Light Pink	Carbonation has started, increasing risk of corrosion
P4 SIDE WALL		Light Pink	Carbonation has started, increasing risk of corrosion,
P4/RHS/233+515/MNB/3		Light Pink	Carbonation has started, increasing risk of corrosion
P5/RHS/233+515/MNB/2		Pink	Carbonation has not started yet.
P5/RHS/233+515/MNB/1		Light Pink	Carbonation has started, increasing risk of corrosion
P3		Colour less	Carbonation has occurred, increasing risk of corrosion

Summary: Carbonation test were performed on the core samples taken form the various walls and slabs. The overall observation as per IS 516 Part5 section3:2021 is that the Carbonation in concrete has started, which is increasing the risk of corrosion in the reinforcement.

4.3 Destructive test results (Core Compressive strength results)

Table: 4.3.1: Core Compressive strength test results

Compressive Strength Results of Core Samples								
ID. NO	**Dimension D x H**	**Area**	**L/D**	**Density**	**Crushing load in kN**	**Core Strength**	**Correction Factor L/d**	**Equivalent Core strength**
	mm x mm	**mm²**		**kg/ m³**	**kN**	**N/mm²**		
P5 SIDE WALL	91 X 161	6500.59	1.77	2410	127.1	19.55	0.98	19.07
P5/RHS/233+ 515/MNB/3	90 X 168	6358.5	1.87	2570	138.5	21.78	0.99	21.48
P4/RHS/253+ 515/2	93 X 158	6789.47	1.7	2393	173.5	25.55	0.97	24.73
P2 wall	90 X 140	6358.5	1.56	2483	140.4	22.08	1	22.08
P4/RHS/253+ 515/1	91 X 177	6500.59	1.95	2498	165	25.38	1	25.38
P4 SIDE WALL	89 X 167	6217.99	1.88	2600	160.5	25.81	0.99	25.48
P4/RHS/233+ 515/MNB/3	89 X 178	6217.99	2	2598	139	22.35	1	22.37
P5/RHS/233+ 515/MNB/2	90 X 165	6358.5	1.83	2545	132.3	20.81	0.98	20.44
P5/RHS/233+ 515/MNB/1	91 X 175	6500.59	1.92	2485	127.2	19.57	0.99	19.41
P3	90 X 160	6358.5	1.78	2553	139	21.86	0.98	21.34

Summary: 10 nos. core samples were extracted and tested to determine the actual in-situ compressive strength. Equivalent Core Strength: The strength values ranged from 19.07 N/mm² to 25.48 N/mm². Statistical Breakdown: Minimum Strength: 19.07 N/mm² (P5 Side Wall), Maximum Strength: 25.48 N/mm² (P4 Side Wall), Average Strength: Approximately 22.18 N/mm². The majority of the samples (7 out of 10) demonstrated a strength greater than 21 N/mm².

5 COMPARATIVE STRUCTURAL DESIGN (CFRP vs. GFRP)

5.1 Design Philosophy:

To address the crack width failure, the retrofitting design focuses on increasing the axial stiffness (EA) of the slab soffit. We compare two materials:

1. Carbon Fiber Reinforced Plate(CFRP): High Strength, High Stiffness.
2. Glass Fiber Reinforced Plate (GFRP): Moderate Strength, Low Stiffness.

Design Data taken for both the materials used is:
Effective Span = 6.0 m
Test Load (W) = 450 kN (45 Tonnes)
Design Moment (M_u =WL/4) = 675 kNm
As per ACI 440 R-17 the CFRP and GFRP plate may designed to provide the 30% strength of that material. And the Deficit strength of the member is 20% and the deficit strength to be carried by the FRP is (assumed to be 20% of 675 kNm) M_{frp} = 135 kNm.

5.2 Material properties comparison:

Table: 5.1: CFRP and GFRP Properties

Properties	CFRP	GFRP
Tensile Strength	2800 MPa	600 MPa
Modulus of Elasticity	165000 MPa	26000 MPa
Thickness of Each layer	1.2 mm	1.2 mm
Width of plate	100 mm	100 mm

5.3 Design of CFRP Strengthening:

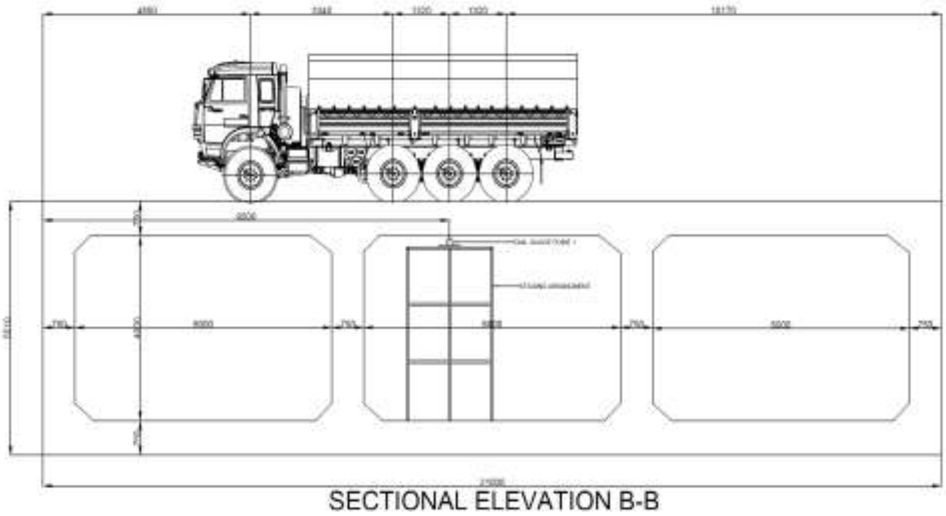


Figure 5.1: Cross Sectional Details of the Box Culvert

Step1: Design data: The overall thickness of the slab is 750mm.
Then,

The overall depth of slab D =750mm
Effective Cover of the slab d' = 50mm
Effective depth of the slab d = D - d' = 750-50 = 700mm

The general formula for the lever arm in Limit State Design is:

$$z = d - 0.42\, x_u$$

where x_u is the depth of actual neutral axis. And for Fe-415 grade steel $x_u = 0.48d$.

Hence Lever arm z is:

$$z = d - 0.42\, x_u = d\,(1-0.42\, x_u)$$
$$z = 700\,(1- 0.42 * 0.48)$$
$$z = 559 \text{ mm (approx.)}$$

Step 2: Calculate the Tensile force (T_f) Transmitting to the CFRP Plate

$$T_f = M_{frp} / z = 135 \times 10^6/559 = 241503 \text{ N}$$

Step 3: Area required for limiting strain to 0.008 to prevent debonding:

Design strength of CFRP f_{design} = modulus of elasticity * strain = E * strain

$$f_{design} = 165000 * 0.008 = 1320 \text{ MPa}$$

Hence Area required of CFRP $A_{req} = 241503/1320 = 183 \text{ mm}^2$

Step 4: Layer determination using 100 mm wide strips (100 * 1.2 = 120 mm^2 / strip) layers = 183/120 = 1.52 = provide 2 layers of CFRP in each line.

5.4 Design of GFRP Strengthening:

Step 1: design data is same for the CFRP plate hence stiffness equivalence since the failure mode is cracking, we must match the stiffness of the CFRP solution, not just the strength.
Then,

Area of GFRP * Modulus of Elasticity of GFRP = Area of CFRP * Modulus of Elasticity of CFRP

$$A_{GFRP} * E_{GFRP} = A_{CFRP} * E_{CFRP}$$

Hence, A_{GFRP} required = (183 * 165000)/ 26000

$$A_{GFRP} = 1162 \text{ mm}^2.$$

Step 2: Layer determination layers = 1162 /120 = 9.68. approx. 10 layers of GFRP plates needs to be provided.

5.5 Cost Benefit Analysis & Selection

Table 5.2: Cost comparison CFRP Vs GFRP

Cost Component	CFRP (2 Layers)	GFRP (10 Layers)
Material Rate (Approx)	₹ 4,500 / m^2	₹ 820 / m^2
Material Total	₹ 9,000/ m^2	₹ 8200 / m^2
Labor Rate (Approx)	₹ 500 / layer	₹ 500 / layer

Labor Total	₹ 1,000/ m^2	₹ 5000 / m^2
Grand Total	₹10000// m^2	₹ 13200 / m^2
Total material required (cell size is 6m*6m = 36m^2) for 6 cell box culvert = 6*36 = 216 m^2		
Total Cost Required	₹2160000/-	₹ 2851200/-

Discussion: Although Glass Fiber GFRP is cheaper by weight, the requirement for 10 layers to match the stiffness of Carbon Fiber CFRP makes it 32% more expensive to install. Furthermore, applying 10 layers overhead is technically infeasible due to gravity and resin curing issues. Hence CFRP strengthening is more economical and viable solution for this structure.

CONCLUSION

Based on the detailed investigation, load testing, and comparative design analysis of the RCC Box Culvert on NH-6, the following conclusions are drawn:

1. Structural Diagnosis (Elastic Recovery): The full-scale Bridge Load Test (45T) demonstrated a deflection recovery of 100% after 24 hours of load retention. As per IRC SP-51 acceptance criteria it signifies that the primary reinforcement has retains its elastic behaviour slab and confirms that the reinforcement not yielded yet.
2. Serviceability check against failure (Crack Widths): Despite satisfactory elastic recovery, tension crack 0.3mm wide observed in slab which exceeds the serviceability limit states. It indicates that the long-term durability of the deck slab and possible corrosion in deck slab reinforcement is possible.
3. Concrete Integrity: As per the NDT test findings the concrete quality is satisfactory (as per Ultra pulse velocity test and Rebound hammer test) is equivalent to M-30 grade. As per above findings the complete replacement of culvert is unnecessary and uneconomical, hence the retrofitting is the most viable solution for this structure.
4. The main rehabilitation strategy were planned to control the crack widths to increase the stiffness of the deck slab not the ultimate load carrying capacity of deck slab. This specific constraint heavily favoured materials with a high Modulus of Elasticity.
5. The comparative analysis revealed that Carbon Fiber (CFRP) has a stiffness (E = 165 GPa) approximately 6.35 times higher than Glass Fiber (GFRP, E = 26 GPa). To achieve equivalent crack control, the design required 10 layers of GFRP compared to only 2 layers of CFRP, hence it is observed that the CFRP is better option.
6. Feasibility: installing 10 layers of GFRP overhead is operationally risky and labour-intensive. The installed cost of the GFRP system is 32% higher than the CFRP system due to labor costs as well as the raw material cost of GFRP is lower but 32% higher than the CFRP system (₹13,200 vs. ₹10,000 per m^2).

Final Recommendation: This above study concluded that the application of CFRP plates with epoxy grouting is more reliable and economical solution than GFRP plate.

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