

ANALYSIS OF PRESTRESSED CONCRETE BEAMS AFTER RETROFITTING USING JACKETING TECHNIQUE

A Thesis

Submitted towards the Requirement for the Award of the Degree of

Doctor of Philosophy

In

Civil Engineering

Under the Faculty of Engineering & Technology

By

Ankur Verma

ENROLLMENT NO- 161555717569

Under the Supervision of

Dr Mahesh Babu



2025

P.K. UNIVERSITY

NH-27, Vill. Thanra (P.O.-DINARA),

Shivpuri M.P. India-473665 www.pkuniversity.edu.in

Shivpuri (M.P.), India-473665



P.K.UNIVERSITY
SHIVPURI (M.P.)

University Established Under section 2F of UGC ACT 1956 Vide MP Government Act No 17 of 2015

FORWARDING LETTER OF THE HEAD OF INSTITUTION

The PhD thesis entitled “**Analysis of Prestressed Concrete Beams After Retrofitting Using Jacketing Technique**” submitted by **Mr Ankur Verma (Enrollment No: 161555717569)** is forwarded to the University in six copies. The candidate has paid the necessary fees, and there are no dues outstanding against him.

Seal & Signature of the Head of the Institution

Date:

Place:



P.K.UNIVERSITY
SHIVPURI (M.P.)

University Established Under section 2F of UGC ACT 1956 Vide MP Government Act No 17 of 2015

CERTIFICATE OF THE SUPERVISOR

This is to certify that the work entitled “**Analysis of Prestressed Concrete Beams after Retrofitting using Jacketing Technique**” is a piece of research work done by **Mr Ankur Verma (Enrollment No: 161555717569)**.

Under My Guidance and Supervision for the degree of Doctor of Philosophy in Civil Engineering, PK University (M.P) India.

I certify that the candidate has put an attendance of more than 240 day with me. To the best of my knowledge and belief the thesis:

I –Embodies the work of the candidate himself/herself.

II – Has duly been completed.

III –Fulfil the requirement of the ordinance relating to the Ph.D. degree of the University.

Signature of the Supervisor

Dr A. Mahesh Babu

Date:



P.K.UNIVERSITY
SHIVPURI (M.P.)

University Established Under section 2F of UGC ACT 1956 Vide MP Government Act No 17 of 2015

DECLARATION BY THE CANDIDATE

I declare that the thesis entitled “**Analysis of Prestressed Concrete Beams after Retrofitting using Jacketing Technique**” is my own work conducted under the supervision of **Prof. (Dr.) A. Mahesh Babu** at Department of Civil Engineering, PK University, Shivpuri, MP, India.

Approved by Research Degree Committee. I have put more than 240 days of attendance with supervisor at the center.

I further declare that to the best of my knowledge the thesis does not contain my part of any work has been submitted for the award of any degree either in this University or in any other University without proper citation.

Signature of the candidate

(Enrollment No- 161555717569)

Date:

Place:

R.D.C. LETTER



P.K. UNIVERSITY
SHIVPURI (M.P.)

University Established Under section 2f of UGC ACT 1956 Vide MP Government Act No 17 of 2015

Ref no: PhD/ PKU/ 2023 / RO-Ext / 034/05

Date: 04/02/23

To

Mr. ANKUR VERMA

Research Scholar -2021-22

Enrollment no: 161555717569

Dept. of Civil Engineering

Faculty of Engineering & Technology

Sub: R.D.C Meeting on: 04/02/2023.

Dear Candidate,

This is to inform you that R.D.C Meeting regarding your Ph.D. Research work was held on 04/02/2023.

The following details are decided about your Ph.D. research work.

1. Title of Thesis: **"ANALYSIS OF PRESTRESSED CONCRETE BEAMS AFTER RETROFITTING USING JACKETING TECHNIQUE"**
2. Guide / Supervisor: **Dr.A.Mahesh Babu**, Professor.
3. Start of Research work 04/02/2023.

Registrar 04/02/23

P.K. University
SHIVPURI (M.P.)

ADDRESS: VILL: THANRA, TEHSIL: KARERA, NH-27, DIST: SHIVPURI, M.P. 473665,
MOB: 7241115088, Email: registrar.pkuniversity@gmail.com

PLAGIARISM REPORT



P.K. UNIVERSITY
SHIVPURI (M.P.)

University Established Under section 2F of UGC ACT 1956 Vide MP Government Act No 17 of 2015

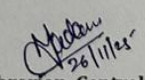
CENTRAL LIBRARY

Ref. No. PKU/C.LIB /2025/PLAG. CERT./229

Date: 26.11.2025

CERTIFICATE OF PLAGIARISM REPORT

1. Name of the Research Scholar : Ankur Verma
2. Course of Study : Doctor of Philosophy (Ph.D.)
3. Title of the Thesis : Analysis of Prestressed Concrete Beams after Retrofitting Using Jacketing Techniques
4. Name of the Supervisor : Dr. Mahesh Babu
5. Department : Civil Engineering
6. Subject : Civil Engineering
7. Acceptable Maximum Limit : 10% (As per UGC Norms)
8. Percentage of Similarity of Contents Identified : 4%
9. Software Used : Drillbit
10. Date of Verification : 03.07.2025


(Librarian, Central Library)
P.K. University, Shivpuri (M.P.)
P.K. University
Shivpuri (M.P.)

ADD: VIL: THANRA, TEHSIL: KARERA, NH-27, DIST: SHIVPURI (M.P.) -473665
MOB: 7241115902, Email: library.pku@gmail.com



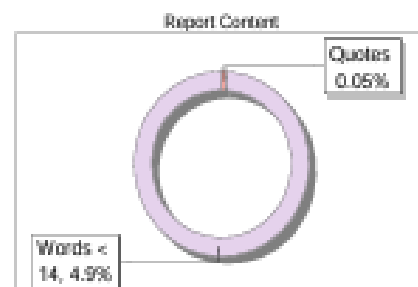
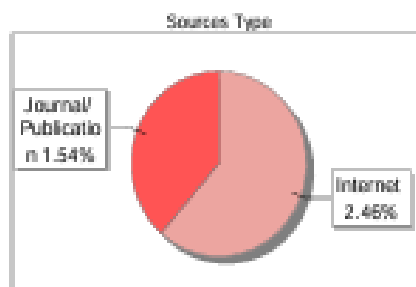
The Report is Generated by DrillBit Plagiarism Detection Software

Submission Information

Author Name	Ankur Verma
Title	ANALYSIS OF PRESTRESSED CONCRETE BEAMS AFTER RETROFITTING USING JACKETING TECHNIQUES
Paper/Submission ID	4063718
Submitted by	library.pku@gmail.com
Submission Date	2025-07-03 12:07:31
Total Pages, Total Words	114, 19788
Document type	Thesis

Result Information

Similarity **4 %**



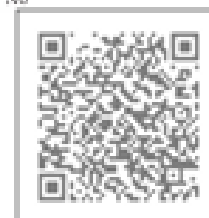
Exclude Information

Quotes	Not Excluded
References/Bibliography	Not Excluded
Source: Excluded < 14 Words	Excluded
Excluded Source	0 %
Excluded Phrases	Not Excluded

Database Selection

Language	English
Student Papers	Yes
Journals & publishers	Yes
Internet or Web	Yes
Institution Repository	No

A Unique QR Code can be View/Download/Share Pdf File



COPYRIGHT TRANSFER CERTIFICATE

**Title of the Thesis: Analysis of Prestressed Concrete Beams After Retrofitting
Using Jacketing Technique**

Name of Candidate: ANKUR VERMA

COPYRIGHT TRANSFER

**The undersigned hereby assigns to the PK University, Shivpuri (M.P.), all
copyrights that exist in and for the above thesis submitted for the award of the
Ph.D. Degree.**

Date: _____

ANKUR VERMA

Ph.D. Scholar

(Civil Engineering)

NOTE: However, the author may reproduce/publish or authorise others to reproduce material extracted verbatim from the thesis or a derivative of the thesis for the author's personal use, provided that the source and the University copyright notice are indicated.

ACKNOWLEDGEMENT

*This thesis was made possible through the invaluable guidance and support of several individuals who have played a significant role in its preparation and successful completion. I would like to express my heartfelt gratitude to my supervisor, **Dr Mahesh Babu**, for his unwavering support, encouragement, and insightful feedback throughout this research project. I am deeply grateful to my Gurudev, **Dr Rajesh Bhargava**, whose constant encouragement, personal mentorship, and unwavering support have guided me at every step of my academic journey.*

*I would like to express my heartfelt gratitude to the Hon'ble Vice Chancellor, **Dr Yogesh Chandra Dubey** and Hon'ble Pro-Vice Chancellor, **Prof Mukesh Chansoriya**, for their inspiring leadership and encouragement. A special note of thanks to **Dr Aiman Fatima** for her invaluable guidance and constant support throughout my thesis work. I am also sincerely grateful to **Dr Bhaskar Nalla** for providing the necessary facilities for the smooth completion of this research work.*

*My beloved parents, **Dr Asha Verma & Dr Rajeev Verma**, whose unwavering love and constant encouragement have been my greatest strength. My heartfelt thanks to my dear sister, **Dr Pranshuta Verma**, & brother-in-law, **Dr Aditya Suman**, and my friend Vivekananda Vyas, for their endless support, motivation, and affection throughout the journey.*

*I want to thank my Chacha & Chachi, **Mr Sanjeev Verma & Mrs Rashmi Verma**, my Mama & Mami, **Mr Ashok Kelde & Mrs Usha Kelde**, and my lovely siblings **Yash, Utkarsh, Yamu & Sezi** for their constant support. Lastly, thank you to a joyful, cheerful companion in our family, **Coffee**, for your tail-wagging motivation, & soulful eyes of Belief.*

*Without all their endless love & unwavering trust, I would not have been able to enjoy this little achievement today. May **Pitambra Mai** bless us all.*

Ankur Verma

I would like to dedicate my thesis to my parents

Dr Asha Verma & Dr Rajeev Verma

INDEX

CHAPTER 1 INTRODUCTION		
1.1	Background	1
1.2	Prestressed Concrete	2
	1.2.1 Terminology	2
	1.2.2 Types of Prestressed Concrete	4
	1.2.3 Materials Used for Prestressed Concrete	7
	1.2.4 Applications of Prestressed Concrete	8
	1.2.5 Advantages of Prestressed Concrete	8
	1.2.6 Challenges of Prestressed Concrete	11
	1.2.7 Recent Developments in Prestressed Concrete	11
1.3	System and Characteristics of Prestressed Concrete	12
	1.3.1 System of Prestressed Concrete	12
	1.3.2 Characteristics of Prestressed Concrete	14
1.4	Term Associated with Retrofitting	17
1.5	Need of Retrofitting	21
1.6	Fundamentals of Jacketing	25
	1.6.1 Objectives of Jacketing	25
	1.6.2 Types of Jacketing	26
	1.6.3 Procedure for Jacketing	27
	1.6.4 Advantages of Jacketing	29

	1.6.5	Limitations of Jacketing	29
	1.6.6	Applications of Jacketing	30
1.7	Significance of the Study		30
1.8	Aim and Scope of the Study		33
	1.8.1	Aim of the Study	33
	1.8.2	Scope of the Study	34
1.9	Motivation		37
1.10	Structure of the Thesis		40
CHAPTER 2 REVIEW OF LITERATURE			
2.1	General Overview		42
2.2	Behaviour of Reinforced Concrete Beams		44
2.3	Behaviour of Prestressed Concrete Beams		48
2.4	Conclusion of Literature Review		64
	2.4.1	Prestressing Methods	64
	2.4.2	Literature Review Insights	64
	2.4.3	Modern Developments	65
	2.4.4	Retrofitting Techniques	65
	2.4.5	Future Directions	66
2.5	Research Gap		66
2.6	Problem Identification		69
2.7	Purpose of the Study		71
2.8	Research Objective		73
2.9	Summary		74

CHAPTER 3 METHODOLOGY		
3.1	General	75
3.2	Properties of Prestressed Concrete Beams	75
3.3	Retrofication of Prestressed Concrete Beams	78
	3.3.1 Trial Configuration	79
	3.3.2 Carrying out	80
	3.3.3 Flow chart	81
	3.3.4 Pilot Project	82
	33.5 Supplies	85
	3.3.6 Design Details of Specimens	88
	3.3.7 Specimen Preparation	88
	3.3.8 Specimen Testing	90
	3.3.9 Summary	92
CHAPTER 4 RESULT AND DISCUSSION		
4.1	Load Carrying Capacity	93
4.2	Change of Location	95
4.3	Crack Pattern and Failure Mode	98
4.4	Remarks	102
CHAPTER 5 CONCLUSIONS AND FUTURE WORK		
5.1	Conclusions	104
5.2	Future work	106
REFERENCES		108
APPENDIX		121

LIST OF TABLES

No.	Title	Page No.
2.1	Comparative Study of Research Papers	59
3.1	Details of Prestressed Concrete Beams	79
3.2	Geometrical And Steel Reinforcement Characteristics of Initial Beams	84
3.3	Material properties of the initial concrete beam and the prestressing strand	84
3.4	Geometrical and steel reinforcement characteristics of retrofitted prestressed concrete beams	86
3.5	Mix design proportion (kg/m ³) of conventional normal concrete	88
3.6	Mix design proportion (kg/m ³) of micro-concrete	89
3.7	Steel reinforcement test results	89
4.1	Load Carrying Capacity and Failure Modes of Strengthened Single-Strand Prestressed Concrete Beams	95
4.2	Load Carrying Capacity and Failure Modes of Strengthened Double-strand Prestressed Concrete Beams	95

LIST OF FIGURES

No.	Title	Page No.
1.1	Tendon	3
1.2	Anchorage	4
1.3	Pre-tensioning Concrete	4
1.4	Post-tensioning Concrete	5
1.5	Precast Sections	9
1.6	Pre-tensioning of Prestressed Concrete Beam	12
1.7	Post-tensioning of Prestressed Concrete Beam	13
1.8	Concrete Jacketing	27
1.9	Steel Jacketing	28
1.10	FRP Jacketing	28
1.11	Composite Jacketing	29
3.1	Details for Beam P1 Q1 R1	75
3.2	Details for Beam P2 Q2 R2	76
3.3	Details of Wooden Mould	77
3.4	Details of HTS Wire	77
3.5	Compressive Strength Testing Machine	78
3.6	Three-sided jacketing and four-sided jacketing of the beam	79
3.7	Cross-sectional details for Single and Double-strand Prestressed Concrete Beams	83

3.8	Prestressed concrete beams with single prestressing strand (b) Prestressed concrete beams with double prestressing strand.	84
3.9	Cross section of retrofitted prestressed concrete beams (a) beam P1 (b) beam P2 (c) beam Q1 (d) beam Q2	89
3.10	Jacketing Procedure (a) treatment of beam surface (b) reinforcement for beams (c) beams in wooden mould (d) concrete placing in moulds (e) curing of beams (f) specimen ready for testing	90
3.11	Loading frame in the laboratory	92
4.1	Load carrying capacity of strengthened prestressed concrete beams	95
4.2	Comparison of Load Deflection Curves for Prestressed Concrete Beams with and without Jacketing	98
4.3	Shows the crack pattern for (a) beam P-1, (b) beam Q-1, (c) beam R-1	100
4.4	Shows the crack pattern for (a) beam P-2, (b) beam Q-2, (c) beam R-2	102

LIST OF ABBREVIATIONS

A	Cross-sectional area of the member
A_c	Area of concrete
e	Eccentricity
E_c	Young's modulus for concrete
E_s	Young's modulus for the tendon
f_s	Compressive stress induced in concrete
f_c	original prestress in concrete
f_{ck}	specified characteristic compressive strength at 28-day
I	Moment of inertia of beam
L	Effective span of PC beam
l	Length of the tendon
M	Bending moment at the section
m	Modular ratio
Ø	Diameter of steel bars
P	Prestressing forces supplied by the tendon
S_c	Specific gravity of cement
V	Absolute volume of concrete
W	Point load at midspan on the beam
μ	Coefficient of friction in the curve
Δf_c	Loss of prestress due to elastic shortening of concrete
Δf_s	Loss of prestress due to deformation, slip

ABSTRACT

The purpose of retrofitting is to increase the strength of existing structural members because of damage to the structural members or due to an increase in service load on structural members. In this study, the overall review of the change in strength parameters and ductility behaviour analysis of Prestressed concrete beams when retrofitted with concrete jacketing. In this study, a total of 6 prestressed concrete beams with a cross-section of 100 mm x 150 mm and an overall length of 1200 mm are used. The prestressed concrete beams are divided into two groups based on the number of prestressing strands placed in the beam. The 2 prestressed concrete beams are strengthened using M-35 concrete mix, and the 2 prestressed concrete beams are strengthened using microconcrete with steel reinforcement all around, respectively. The remaining 2 prestressed concrete beams are used as control beams. After completion of the jacketing process and curing period, the beams are experimentally tested on the centre point loading system. The observations for ultimate load, deflection, failure modes and crack pattern are noted. The effectiveness of different jacketing techniques for strengthening prestressed concrete beams is analysed and reported. The outcome of the study shows that load load-carrying capacity of jacketed prestressed concrete beams using microconcrete was greatly increased by 350 to 380 % and load carrying capacity of jacketed prestressed concrete beams using conventional concrete mix was greatly increased by 200 to 220 % to non-jacketed prestressed concrete beams.

Keywords: Retrofitting, Jacketing, Prestressed Concrete, Microconcrete

CHAPTER 1

INTRODUCTION

1.1 Background

Prestressed concrete beams are structural elements in which internal stresses are introduced before external loads are applied. This process enhances the beam's ability to resist tensile stresses, allowing for longer spans, reduced cross-sectional areas, and improved serviceability and durability compared to conventional reinforced concrete beams.

The concept of prestressing was pioneered by French engineer Eugène Freyssinet in the early 20th century. Freyssinet's work in the 1920s laid the foundation for modern prestressed concrete, leading to the development of techniques and materials that made the widespread use of prestressed concrete beams feasible.

Prestressed concrete beams represent a significant advancement in civil engineering, providing enhanced strength and durability compared to conventional reinforced concrete. This technology, which emerged in the early 20th century, involves the preapplication of compressive stress to the concrete, counteracting the tensile stresses that occur during service. As a result, prestressed concrete beams exhibit improved performance characteristics, such as higher load-carrying capacity, reduced crack width, and increased span lengths.

The fundamental principle of prestressing involves inducing internal stresses in concrete by tensioning high-strength steel tendons before applying external loads. This enhances the concrete's ability to resist tensile stresses and cracking. Prestressing is achieved through two primary methods: pre-tensioning and post-tensioning.

In pre-tensioning, high-strength steel tendons are stretched and anchored against a fixed formwork before the concrete is poured. Once the concrete is cast and gains sufficient strength, the tension in the tendons is released, transferring compressive forces to the concrete through bond. In contrast, post-tensioning involves placing the tendons within ducts embedded in the concrete. After the concrete hardens, these tendons are tensioned using hydraulic jacks and anchored at the ends, applying compressive stress and enhancing the structural capacity of the concrete element.

Over the years, extensive research has been conducted to refine the design and construction techniques of prestressed concrete beams. This includes investigations into various tendon materials, anchorage systems, and concrete compositions. Optimising these components is crucial for achieving the desired mechanical properties and ensuring long-term durability.

Additionally, advanced analytical methods and computational tools have been developed to predict the behavior of prestressed concrete beams under different loading conditions. These tools help engineers design safer and more efficient structures by accurately modeling the complex interactions between the concrete and the prestressing tendons.

The application of prestressed concrete beams spans various types of structures, including bridges, buildings, and other infrastructure projects. Their ability to withstand higher loads and longer spans makes them particularly suitable for largescale and demanding projects. Furthermore, the use of high-performance materials and innovative construction techniques continues to push the boundaries of what can be achieved with prestressed concrete technology.

1.2 Prestressed Concrete

To resist stress from external loads in the correct manner over the service term, pre-stressed concrete is a kind of concrete in which initial compression is applied before applying the external load.

High-strength steel wire or alloys (referred to as "tendons") embedded in the concrete portion cause this initial compression. Prestressing is applying pre-compression to manage the stresses that arise from external loads below the neutral axis of the beam tension that exceeds the plain concrete's allowable limitations. The compressive stress below the neutral axis or across the beam c/s will be caused by the pre-compression that is applied, which may be either axial or eccentric. resulting in neither compression nor tension.

Prestressed concrete is essentially concrete that has had appropriate internal stresses added to it to counteract the stresses caused by external loads to the necessary extent.

1.2.1 Terminology

A. Tendon

A stretched component that gives prestress to concrete in a structural member.



Figure 1.1: Tendon

(Source: <https://www.rgmcet.edu.in/assets/img/departments/CIVIL/materials/R15/3-2/PSC/PSC%20UNIT%203.pdf>)

B. Anchorage

A tool that is often used to allow the tendon to create and preserve prestress in concrete.



Figure 1.2: Anchorage

(Source: <https://www.rgmccet.edu.in/assets/img/departments/CIVIL/materials/R15/3-2/PSC/PSC%20UNIT%203.pdf>)

1.2.2 Types of Prestressed Concrete

A. Pre-tensioning

A technique for prestressing concrete where the tendons are pulled taut prior to the concrete's placement. Concrete is introduced using this approach by means of a link between steel and concrete. This process involves first tensioning wires or tendons and then pouring concrete.



Figure 1.3: Pre-tensioning Concrete

(Source: <https://tutorialstipscivil.com/what-is-pre-tensioned-concrete/>)

It improves the bonding strength between the concrete and tendon. Tensions are passed directly and the tendons are shielded from corrosion as a consequence. When the concrete hardens, the tension in the attached and stretched tendon is transmitted to the material. The tendon then attempts to return to its initial length, but the concrete's bond resists it; as a result, compressive force is induced in it.

B. Post-tensioning

Comparable to pre-stressing, except that tendons are tensioned after concrete is poured. After the member's tendon is positioned appropriately, casting is completed. The tendons are tensioned against the concrete by hydraulic jacks after the concrete hardens. Tendons are set in place when they are suitably tensioned in accordance with design. Tension continues when the jacks are removed, applying pressure to the concrete.



Figure 1.4: Post-tensioning Prestressed Concrete

(Source: <https://www.force-s.com/post/understanding-prestressing-pre-tension-or-post-tension>)

This technique is often employed to make monolithic slabs for large-scale home building projects, where difficulties with expanding soil might sometimes arise. In addition, post-tensioned concrete is used in bridge construction.

C. Unbonded Post-tensioning

Compared to bonded post-tensioned concrete, it differs somewhat. It permits unrestricted cable movement. Each tendon is encased in plastic and lubricated for this purpose. Through anchors, the cables distribute stress to the concrete. This has several benefits, such as:

- a. The capacity to strain tendons before attempting repairs.
- b. The capability of individual cable adjustment.

D. Composite Prestressed Concrete

A composite prestressed concrete beam is a structural element formed by combining a precast prestressed concrete component (such as a girder or slab) with a cast in-situ concrete layer, so that the two act together as a single unit under loads. The precast prestressed member, produced under controlled conditions, carries its own weight and construction loads during erection. After installation, an in-situ concrete slab or topping is cast over it and bonded to the precast element, enabling the section to resist service loads as a composite unit.

This method utilises the high quality and immediate strength of precast prestressed members along with the monolithic action and flexibility of in-situ concrete, resulting in greater structural efficiency, reduced material usage, and improved construction speed. Composite prestressed beams are commonly used in bridges, floors, and industrial structures where long spans, high load capacity, and rapid construction are required.

1.2.3 Materials Used

A. Cement

Any of the following types of cement should be used:

- (a) Regular Portland cement that complies with IS 269
- (b) Portland slag cement that complies with IS455.

However, the maximum amount of slag content should be 50%.

- (c) Portland cement with rapid hardening that complies with IS8041.
- (d) Ordinary Portland cement that complies with IS 8112.

B. Concrete

For precast concrete, high compressive strength concrete with a relatively early age and a relatively greater tensile strength than regular concrete is needed. Portland cement, water, admixtures, and fine and coarse aggregates make up the air-entrained concrete for the members. Either air-entraining Portland cement or an authorized air-entraining admixture may be used to achieve the air-entraining characteristic. The percentage of entrained air must neither be less than 4 percent nor more than 6 percent. For the durability requirement, a minimum cement content of 300 to 360 kg/m³ is recommended. As little water as possible should be present.

C. Steel

Steel may include cables, strands, tendons, or high-tensile bars that can be employed for this purpose. Standard hard-drawn steel wire that complies with Parts I and III of IS1785,

- (a) High tensile steel wire bar that complies with IS2090;
- (b) cold drawn indented wire that complies with IS6003
- (c) Stress relieved strand without coating that complies with IS6006

The composition of high strength steel is 0.1% silica, 0.6% manganese, and 0.7 to 0.8% carbon.

1.2.4 Applications

Several applications of pre-stressed concrete in concrete structures are in

- i **Bridges:** Prestressed concrete is extensively used in bridge construction, allowing for longer spans and fewer supports.
- ii **Buildings:** It is used in various building components, such as floors, beams, and columns, to create open spaces and efficient load distribution.
- iii **Industrial Structures:** Tanks, silos, and other industrial structures benefit from the strength and durability of prestressed concrete.
- iv **Infrastructure:** Prestressed elements are used in pavements, pipelines, and other infrastructure projects where high performance is required.

1.2.5 Advantages

When compared to conventional reinforced concrete (RC) without prestressing, prestressed concrete offers a number of benefits. During its service life, a completely prestressed concrete part is often exposed to compression. This fixes a number of concrete's shortcomings. The benefits of a prestressed concrete member over a comparable RC member are briefly discussed in the text that follows. Each impact has a set of advantages.

1) Despite service loads, the section is not cracked

- a. Steel corrosion is reduced; durability is increased.
- b. The whole section is used, resulting in fewer deformations.
- c. Greater moment of inertia provides greater stiffness
- d. A rise in shear strength and better serviceability.
- e. Fit for use in liquid-retaining structures and pressure vessels.
- f. Better resilience and performance under fatigue and dynamic loads.

2) High ratios of span to depth

Prestressing allows for larger span bridges, structures with huge column-free zones, etc. The following lists typical span-to-depth ratio numbers for slabs.

Non-prestressed slab	28:1
Prestressed slab	45:1

Less depth for the same span as an RC member results in a decrease in body weight and enhances the visual attractiveness because of narrower portions with more economical structures.

3) Fit for use in precast building

Precast construction offers several advantages, including rapid construction, improved quality control, and reduced maintenance requirements. It is particularly suitable for repetitive building layouts, making it ideal for mass housing and commercial projects. The use of standardised moulds allows for multiple applications of the same formwork, reducing the overall number of formwork units needed and enhancing efficiency. Additionally, the availability of standard precast forms further streamlines the construction process. Various commonly used precast sections are illustrated in the accompanying diagram, showcasing their versatility and wide applicability in modern construction practices.

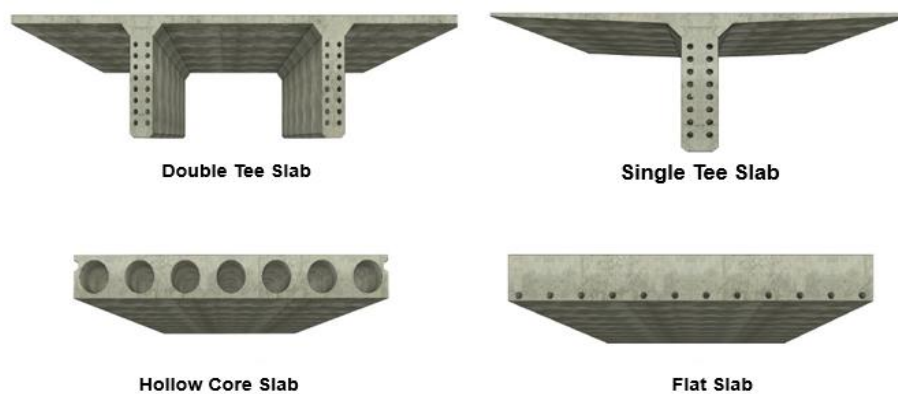


Figure 1.5: Precast Sections

(source: <https://www.nachi.org/gallery/flat/types-of-pre-cast-pre-stressed-concrete-roof-decks-1>)

- 4) Pre-stressed concrete enables a greater span.
- 5) More resistance to shear force is provided by pre-stressed concrete members.
- 6) Under operating stresses, a pre-stressed concrete member is stiffer than a reinforced concrete member when both have the same depth.
- 7) A smaller cross section is produced by using better strength steel and concrete.
- 8) Greater Load-Bearing Capacity: Prestressed concrete can support heavier loads than non-prestressed concrete components because it counteracts tensile strains.
- 9) Crack Control: Prestressing reduces the likelihood of cracks, resulting in stronger, longer-lasting structures.
- 10) Material Efficiency: Prestressed concrete's superior strength and performance enable the use of less material, which results in lighter and more cost-effective constructions.
- 11) Increased Durability: The structure's overall lifespan and durability are boosted by a decrease in cracking and an increase in strength.
- 12) Greater Design Flexibility: Prestressed concrete allows to the production of more intricate designs, longer spans, and thinner sections, hence offering greater design flexibility.
- 13) Pre-stressed concrete uses the cross-section more effectively than reinforced concrete.
- 14) Pre-stressed concrete has the following key benefits:
 - Better resistance to shear pressures because of the existence of compressive stresses or an eccentric cable profile.
 - Long span structures may be built, which will result in considerable weight savings and make the solution cost-effective.
 - Pre-stressed concrete structures provide considerable notice of impending collapse by exhibiting notable deflection prior to their eventual demise.

- Small changes in prestressing steel, which is suggested for dynamically loaded constructions, improve fatigue strength.
- Eccentric prestressing may counterbalance dead loads in pre-stressed parts.
- Despite service loads, the section is still uncracked.
- High ratios of span to depth
- Fit for use in precast building.

1.2.6 Challenges

Complex Design and Construction: The design and execution of prestressed concrete require precise calculations and skilled labor. Any errors can significantly affect the performance of the structure.

Higher Initial Costs: The initial costs of materials and the specialized equipment required for prestressing can be higher compared to conventional concrete.

Maintenance of Prestress: Ensuring the long-term maintenance of the prestress force is crucial. Loss of prestress due to relaxation, shrinkage, or creep can affect the performance of the structure.

1.2.7 Recent Developments

Advancements in materials and technology continue to improve prestressed concrete. Due to their high strength and resistance to corrosion, advanced composite materials, such as carbon fibre reinforced polymers (cfrp), are becoming more common for tendons.

Additionally, modern computer-aided design and construction techniques are making prestressed concrete more efficient and easier to implement.

1.3 System and Characteristics of Prestressed Concrete

1.3.1 System of Prestressed Concrete

Pre-tensioning is a kind of pre-stretching concrete in which tendons are pulled taut prior to the concrete's placement. With this technique, a link between the steel and concrete gives the concrete prestress. The post-tensioning technique is a way to prestretch concrete by pulling tendons against hard-earned concrete. With this technique, bearings are used to apply prestress to concrete.

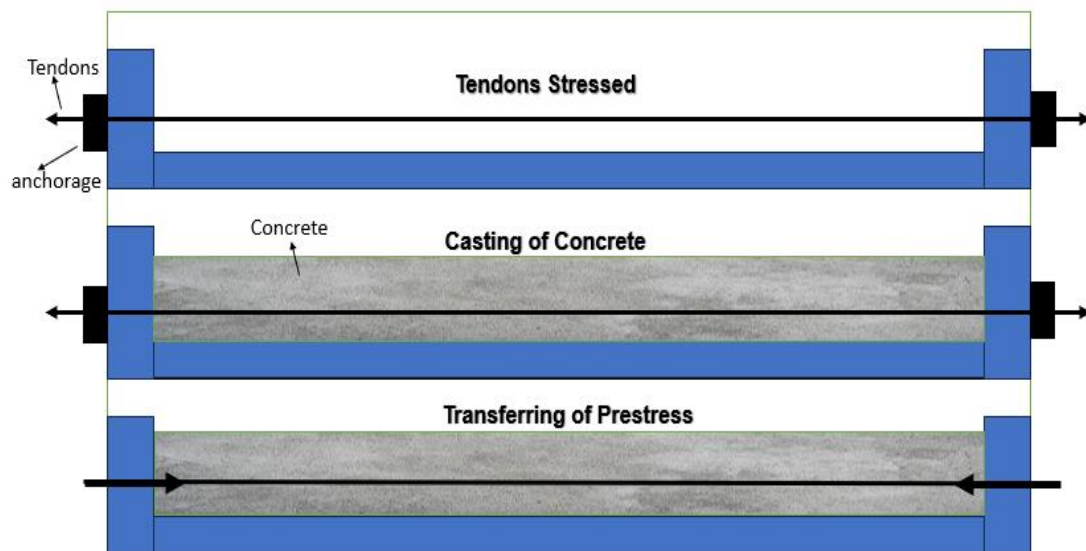


Figure 1.6: Pre-tensioning of Prestressed Concrete Beam

The tendons in a pre-tensioned system are already taut prior to the concrete being cast. The tendon reinforcement is fastened to one end of an abutment and dragged to the other end, which is then fastened to another abutment, using a jack. It's time to pour the concrete. The ends of the reinforcement are freed from the abutments after the concrete has dried and solidified.

Through bond action, the reinforcement that is inclined to revert to its initial length will compress the surrounding concrete.

Thus, the link between the reinforcement and the surrounding concrete is the only mechanism via which the prestress is transferred to the concrete.

The bond between concrete and steel plays a crucial role in the process of pre-tensioning in prestressed concrete structures. A poor bond result in slippage and loss of prestress and will eventually impact the overall performance and durability of the structure.

The factors influencing the bond are as surface texture of steel, the strength of concrete at the transfer of prestress to the member, compaction and curing of the member during and after the construction and the embedment length to transfer the prestress more effectively and efficiently. After the concrete has completely set, the reinforcement in a post-tensioned system is tensioned. First, the beam is cast, leaving ducts for the tendons to be placed. There are many methods to create the ducts: you may use rubber hose, steel spirals, sheet metal tubing, corrugated steel tube left in the concrete, or any other duct forming unit installed in the form work.

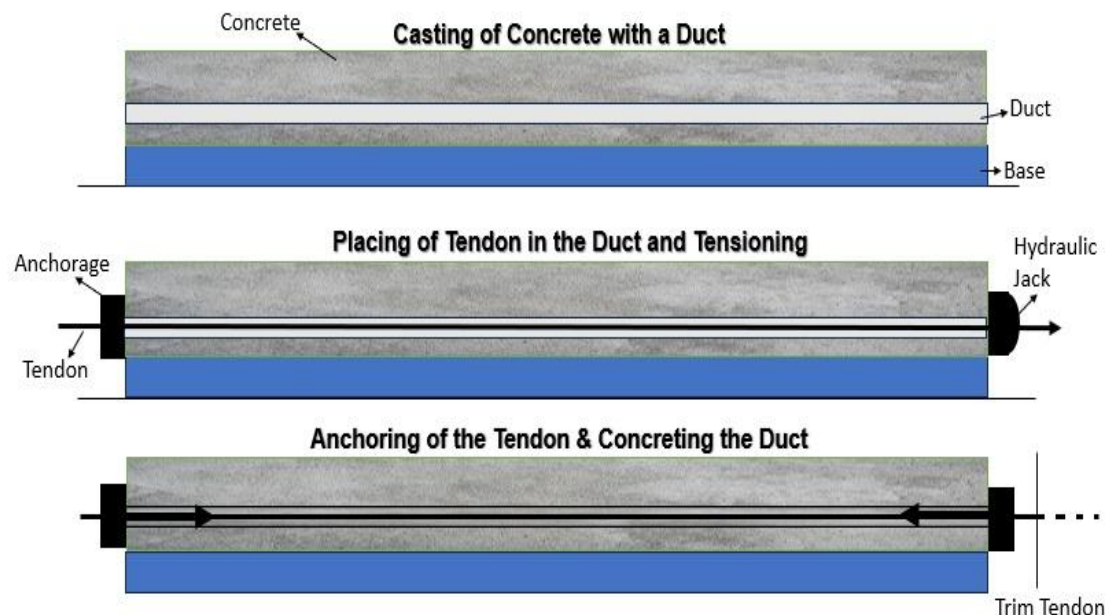


Figure 1.7: Post-tensioning of Prestressed Concrete Beam

The tendon is passed through the conduit once the concrete has strengthened and set. One end of the member is fastened to the other end and has an anchor attached to it. Now, a jack that is butting up against the end of the member pulls on the other end of the tendon.

The jack compresses the concrete and pulls the tendon at the same time. The tendon's end is correctly fastened to the concrete after it has been exposed to the necessary amount of tension. A distribution plate is positioned at either end to prevent excessive bearing stress from breaking the concrete.

1.3.2 Characteristics of Prestressed Concrete

Prestressed concrete is distinguished by several key characteristics that make it highly suitable for a wide range of civil engineering applications. These characteristics enhance its performance, durability, and versatility, allowing it to be used in various structural elements.

A. High Tensile Strength

Explanation: Prestressed concrete effectively counteracts the natural weakness of concrete in tension by introducing compressive stresses. This makes it much stronger in tension compared to conventional reinforced concrete.

Application: This characteristic is particularly beneficial in applications such as long-span bridges, where tensile forces are significant.

B. Improved Load-Bearing Capacity

Explanation: The pre-compression in the concrete allows prestressed elements to carry greater loads and span longer distances without excessive deflection or cracking.

Application: This is crucial for structures like multi-story buildings and large-span roofs.

C. Crack Control and Reduction

Explanation: Prestressing reduces the likelihood of cracks developing under service loads by keeping the concrete in compression. This helps in maintaining the integrity and aesthetics of the structure.

Application: It is especially important in water-retaining structures and liquid storage tanks, where leakage through cracks must be avoided.

D. Material Efficiency

Explanation: Prestressed concrete makes more efficient use of high-strength materials, reducing the overall amount of concrete and steel required. This leads to lighter structures and cost savings.

Application: This efficiency is advantageous in the construction of bridges, where reducing the dead load can lead to smaller foundations and lower overall project costs.

E. Enhanced Durability

Explanation: The reduction of cracks and the use of high-quality materials contribute to the increased durability of prestressed concrete structures. They are more resistant to environmental degradation, such as corrosion and freeze-thaw cycles.

Application: This is particularly beneficial in harsh environments, such as coastal areas or regions with severe weather conditions.

F. Design Flexibility

Explanation: Prestressed concrete allows for innovative architectural and structural designs, including longer spans, thinner sections, and complex shapes.

Application: This flexibility is utilized in the construction of aesthetically pleasing structures such as modern bridges, large stadiums, and auditoriums.

G. Reduced Deflections

Explanation: The initial compressive stresses in prestressed concrete minimize deflections under service loads, ensuring that the structure maintains its intended shape and functionality.

Application: This characteristic is critical in floor systems and bridges, where excessive deflection could lead to functional or aesthetic issues.

H. High Resistance to Fatigue

Explanation: Prestressed concrete structures exhibit superior performance under cyclic loading conditions due to the pre-compression in the concrete.

Application: This is important in applications such as railway sleepers and highway bridges, which are subjected to repeated loading over time.

I. Efficient Use of Construction Materials

Explanation: The high-strength steel tendons and high-quality concrete used in prestressed concrete structures make efficient use of materials, optimizing the strength-to-weight ratio.

Application: This efficiency is particularly valuable in high-rise buildings and longspan structures, where minimizing material usage is a key consideration.

J. Fire Resistance

Explanation: Prestressed concrete generally has good fire resistance properties due to the inherent characteristics of concrete and the protective cover over the steel tendons.

Application: This is beneficial in buildings and infrastructure where fire safety is a critical concern.

Prestressed concrete combines high strength, durability, and versatility, making it an indispensable material in modern civil engineering. Its ability to handle higher loads, control cracking, and allow for innovative designs significantly enhances the performance and longevity of structures. These characteristics make prestressed concrete a preferred choice for a wide range of applications, from bridges and buildings to industrial structures and infrastructure projects.

1.4 Terms Associated with Retrofitting

1. Retrofitting

- Definition: The process of modifying existing structures to improve their performance, particularly in terms of strength, stability, and durability. Retrofitting is often undertaken to enhance the structural integrity of buildings and infrastructure to meet current standards and resist new types of loads, such as seismic activity.
- Purpose: To extend the life of a structure, improve safety, and ensure compliance with updated building codes and regulations.

2. Structural Assessment

- Definition: A comprehensive evaluation of an existing structure to determine its current condition, performance, and any deficiencies. This involves inspecting and analysing the building materials, structural components, and overall stability.
- Purpose: To identify the need for retrofitting and to guide the development of an appropriate retrofitting strategy.

3. Seismic Retrofitting

- Definition: The process of strengthening existing buildings and structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes.
- Techniques: Common techniques include base isolation, addition of shear walls, bracing, and reinforcement of joints.

4. Jacketing

- Definition: Jacketing is a retrofitting technique that involves encasing existing structural elements such as columns, beams, or slabs with materials like concrete, steel, or fibre-reinforced polymers to improve their load-carrying capacity, ductility, and resistance to seismic forces.
- Materials Used: Concrete, steel, or fiber-reinforced polymer (FRP) composites.

5. Base Isolation

- Definition: A seismic retrofitting technique that involves decoupling a structure from ground motion by installing flexible bearings or isolators at its base. This reduces the energy transferred from the ground to the structure during an earthquake.
- Types: Elastomeric bearings, sliding bearings, and hybrid systems.

6. Shear Wall

- Definition: A structural wall that is designed to resist lateral forces such as wind or seismic loads. Shear walls are often added or reinforced during retrofitting to improve a building's lateral stiffness and strength. They are particularly crucial in high-rise structures and buildings located in seismic-prone areas.
- Materials: Reinforced concrete, steel, or masonry.

7. Bracing

- Definition: The addition of diagonal supports (braces) to a structural frame to increase its stability and resistance to lateral loads. Bracing can be applied internally or externally.
- Types: X-bracing, K-bracing, and eccentric bracing.

8. Fibre Reinforced Polymer (FRP) Composites

- Definition: High-strength composite materials made of fibers embedded in a polymer matrix. FRP composites are used in retrofitting to strengthen and rehabilitate structural elements without significantly increasing their weight.
- Applications: Wrapping columns, beams, and walls to enhance their load-bearing capacity and ductility.

9. Shotcrete

- Definition: : Shotcrete is a technique of applying concrete or mortar pneumatically through a hose at high velocity onto prepared surfaces, enabling it to compact and adhere effectively without the need for traditional formwork. It is widely used in retrofitting to repair, rehabilitate, and strengthen deteriorated concrete elements, particularly in hard-to-reach or irregular areas.
- Advantages: Rapid application, good bonding, and minimal formwork requirements.

10. Post-Tensioning

- Definition: A method of reinforcing concrete by tensioning steel tendons after the concrete has hardened. This technique can be used in retrofitting to enhance the load-carrying capacity and control deflection in existing structures.
- Applications: Strengthening of beams, slabs, and bridges.

11. Structural Health Monitoring (SHM)

- Definition: The use of sensors and data acquisition systems to continuously monitor the condition of a structure. SHM provides real-time information about the structural performance and can detect early signs of damage or deterioration.
- Purpose: To inform maintenance decisions and validate the effectiveness of retrofitting measures.

12. Non-Destructive Testing (NDT)

- Definition: Techniques used to evaluate the properties and condition of materials and structures without causing damage. Common NDT methods include ultrasonic testing, radiography, and ground-penetrating radar.
- Purpose: To assess the integrity of a structure and identify areas that require retrofitting.

13. Structural Reinforcement

- Definition: The addition of materials or structural elements to an existing structure to increase its strength and stiffness. Reinforcement can be achieved through various methods such as adding steel plates, rebar, or composite materials.
- Applications: Strengthening of beams, columns, and slabs.

14. Load Path

- Definition: The route through which loads are transferred from the point of application to the foundation. Understanding the load path is crucial in retrofitting to ensure that new loads are properly distributed and do not compromise the structural integrity.
- Consideration: Ensuring that the retrofitting measures effectively integrate with the existing load path.

15. Anchoring

- Definition: The process of securing retrofitting materials or structural components to the existing structure using mechanical fasteners or adhesives. Proper anchoring is essential to ensure the effectiveness of the retrofitting measures.
- Techniques: Use of bolts, screws, epoxy adhesives, and chemical anchors.

Understanding these terms is essential for professionals involved in the retrofitting of civil engineering structures. Each term represents a critical aspect of the retrofitting process, contributing to the overall goal of enhancing structural performance, safety, and longevity. By applying these concepts effectively, engineers can ensure that existing structures meet modern standards and are capable of withstanding new challenges.

1.5 Need of Retrofitting

Retrofitting of prestressed concrete beams is essential for several reasons, driven by the need to enhance structural performance, safety, and longevity. Despite the inherent strength and durability of prestressed concrete beams, various factors necessitate retrofitting to maintain and improve their functionality. The following points elaborate on the key reasons for retrofitting prestressed concrete beams:

1. Ageing and Deterioration

- **Material Degradation:** Over time, the materials in prestressed concrete beams, such as concrete and steel tendons, may degrade due to environmental exposure, chemical attacks, or fatigue. Retrofitting addresses these issues by restoring or enhancing the material properties.
- **Cracking and Spalling:** Even with prestressing, cracks and spalling can occur due to various reasons, such as overloading or environmental effects. Retrofitting helps to repair and prevent further deterioration.
- **Loss of Prestress:** Over time, prestressed concrete beams may experience a reduction in prestressing force due to creep, shrinkage, or relaxation of tendons. Retrofitting techniques can help restore the desired level of prestress and improve the structural performance of the beam.

2. Increased Load Demands

- **Change in Usage:** The function of a structure may change over time, leading to increased load demands that the original design did not account for. Retrofitting strengthens the beams to accommodate the new load requirements.
- **Code Upgrades:** Updated building codes and standards may impose stricter load and performance requirements. Retrofitting ensures that the beams comply with these new regulations.

3. Seismic Considerations

- **Seismic Vulnerability:** Many older structures were not designed to withstand seismic forces. Retrofitting enhances the seismic resistance of prestressed concrete beams, improving their performance during earthquakes.

- **Ductility and Energy Dissipation:** Retrofitting methods can improve the ductility and energy dissipation capacity of prestressed beams, making them more resilient to seismic events.

4. Damage Repair

- **Accidental Damage:** Structures can suffer damage from accidents, such as vehicle impacts or fires. Retrofitting repairs the damaged beams, restoring their structural integrity and ensuring safety.
- **Structural Deficiencies:** Design or construction errors may lead to structural deficiencies. Retrofitting corrects these issues, enhancing the overall performance of the beams.

5. Environmental Factors

- **Corrosion Protection:** In environments where prestressed beams are exposed to moisture, chlorides, or other corrosive agents, the steel tendons can corrode, compromising the beam's integrity. Retrofitting involves applying protective coatings or barriers to prevent corrosion.
- **Freeze-Thaw Cycles:** In cold climates, freeze-thaw cycles can cause significant damage to concrete. Retrofitting methods like applying surface treatments or adding insulation layers help mitigate these effects.

6. Extending Service Life

- **Prolonging Structural Life:** Retrofitting extends the service life of prestressed concrete beams, delaying the need for complete replacement. This is especially important for critical infrastructure where replacement would be costly and disruptive.
- **Sustainable Practices:** Extending the lifespan of existing structures through retrofitting is more sustainable than demolition and reconstruction, reducing the environmental impact and conserving resources.

7. Enhancing Performance

- **Load Redistribution:** Retrofitting can improve the distribution of loads across a structure, enhancing the performance and efficiency of the prestressed beams.
- **Improving Deflection and Vibration Characteristics:** Over time, beams may exhibit excessive deflection or vibration. Retrofitting methods, such as adding additional prestressing or stiffening elements, help control these issues.

8. Economic Considerations

- **Cost-Effectiveness:** Retrofitting is often more cost-effective than demolishing and reconstructing a structure. It allows for the continued use of existing infrastructure with improved performance.
- **Minimizing Disruption:** Retrofitting can be performed with minimal disruption to the structure's use, which is crucial for essential facilities like hospitals, schools, and bridges.

9. Technological Advancements

- **Adoption of New Materials:** Advances in materials technology, such as fibre-reinforced polymers (FRP), provide new opportunities for effective retrofitting solutions. These materials offer high strength-to-weight ratios and excellent durability.
- **Innovative Techniques:** The development of new retrofitting techniques and tools allows for more efficient and effective strengthening of prestressed concrete beams.
- **Digital Monitoring and Analysis:** Integration of smart sensors and structural health monitoring systems enables real-time assessment of stresses, deflections, and damage in prestressed concrete beams. This technology enhances decision-making for timely maintenance and targeted retrofitting interventions.

Retrofitting of prestressed concrete beams is necessary to address aging and deterioration, accommodate increased load demands, enhance seismic performance, repair damage, protect against environmental factors, extend service life, improve performance, and achieve economic benefits. By implementing appropriate retrofitting methods, engineers can ensure that prestressed concrete beams continue to perform safely and efficiently, meeting modern standards and extending the usability of critical infrastructure.

1.6 Fundamentals of Jacketing

Jacketing is a technique used in civil engineering to strengthen or retrofit existing structures. It involves encasing or wrapping a structural element, such as a column, beam, or wall, with additional material to enhance its load-carrying capacity, improve its durability, or repair damage. Jacketing is commonly employed to address structural deficiencies, upgrade performance, or extend the service life of a structure.

1.6.1 Objectives of Jacketing

Increase Load Capacity: Enhance the strength of structural elements to carry higher loads.

Improve Ductility: Increase the deformation capacity of the structure, making it more resilient to seismic forces.

Repair and Rehabilitation: Address damages due to corrosion, wear, or physical impacts.

Extend Service Life: Enhance the durability and longevity of the structure.

Upgrade to New Standards: Bring older structures in compliance with updated building codes and standards.

1.6.2 Types of Jacketing

(1) Concrete Jacketing

Description: Involves adding a layer of reinforced concrete around the existing structural element.

Application: Commonly used for columns and beams.

Materials: Reinforced concrete with steel rebars or welded wire mesh.

(2) Steel Jacketing

Description: Uses steel plates or sections to encase the structural element.

Application: Suitable for areas with high load requirements and where space constraints limit the use of concrete.

Materials: Steel plates, channels, or angles.

(3) FRP (Fiber Reinforced Polymer) Jacketing

Description: Involves wrapping the structural element with high-strength fiber composites.

Application: Ideal for seismic retrofitting and corrosion-prone environments.

Materials: Carbon fiber, glass fiber, or aramid fiber composites with epoxy resin.

(4) Composite Jacketing

Description: Combines different materials, such as concrete and steel, or concrete and FRP, to leverage the benefits of each.

Application: Used where a combination of strength, ductility, and durability is required.

Materials: A mix of concrete, steel, and/or FRP.

1.6.3 Procedure for Jacketing

- A. **Assessment:** Conduct a detailed inspection and evaluation of the existing structure to identify the deficiencies and determine the requirements for jacketing.
- B. **Design:** Design the jacketing system based on the assessment. This includes determining the type, thickness, and reinforcement details.
- C. **Preparation:** Prepare the surface of the existing structural element. This may involve cleaning, roughening, or applying a bonding agent to ensure good adhesion between the old and new materials.
- D. **D. Installation:**
Concrete Jacketing: Install formwork, place the reinforcement, and pour the concrete.



Figure 1.8: Concrete Jacketing
(Source: https://sslaxmienterprise.com/?page_id=662)

Steel Jacketing: Weld or bolt the steel plates or sections around the structural element.



Figure 1.9: Steel Jacketing

(Source: <https://www.horseen.com/solution/steel-jacketing-of-the-column>)

FRP Jacketing: Apply the fibre sheets or strips, saturate them with resin, and ensure proper wrapping and bonding.



Figure 1.10: FRP Jacketing

(Source: <https://ptbmjp.com/hdpe-composite-jacketing/>)

Composite Jacketing: Follow a combined approach as per the design specifications.

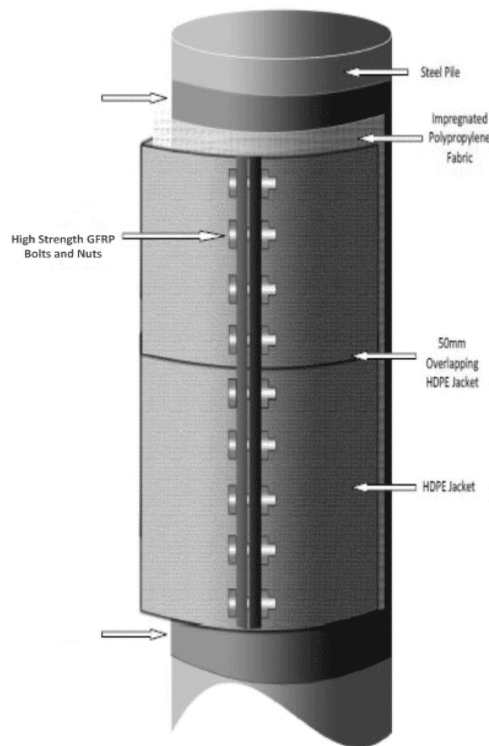


Figure 1.11: HDPE Composite Jacket
(Source: <https://ptbmjp.com/hdpe-composite-jacketing/>)

E. Curing and Finishing: Allow adequate curing time for concrete and ensure proper bonding for steel and FRP systems. Finish the surface as required.

1.6.4 Advantages of Jacketing

1. **Versatility:** Can be applied to various structural elements and materials.
2. **Cost-Effective:** Often more economical than replacing the entire structure.
3. **Minimal Disruption:** Allows for strengthening without significant interruption to the structure's use.
4. **Improved Performance:** Enhances load capacity, ductility, and durability.
5. **Adaptability:** Can be customized to meet specific structural requirements and constraints.

1.6.5 Limitations of Jacketing

1. **Increased Dimensions:** Can lead to increased cross-sectional dimensions, which may be a constraint in space-limited areas.
2. **Weight Addition:** Adds additional weight to the structure, which must be accounted for in the design.
3. **Complexity:** Requires careful design and execution to ensure effectiveness and durability.
4. **Compatibility Issues:** Ensuring compatibility between existing materials and new jacketing materials can be challenging.

1.6.6 Applications of Jacketing

1. **Seismic Retrofitting:** Enhancing the seismic performance of buildings and bridges.
2. **Structural Repairs:** Addressing damage due to corrosion, impact, or wear.
3. **Load Upgrading:** Strengthening columns, beams, and other elements to carry higher loads in industrial or commercial buildings.
4. **Life Extension:** Extending the service life of aging infrastructure, such as bridges, tunnels, and dams.

Jacketing is a fundamental technique in civil engineering for strengthening, retrofitting, and repairing structural elements. Its versatility, cost-effectiveness, and ability to improve structural performance make it a widely used method in various applications. Proper selection of materials and execution methods is crucial to ensure the desired enhancement in strength, durability, and seismic resistance. When applied correctly, jacketing not only restores but can significantly extend the service life of ageing or underperforming structures.

1.7 Significance of the Study

Prestressed concrete beams play a pivotal role in modern civil engineering structures due to their enhanced load-bearing capacity, durability, and versatility. This study on prestressed concrete beams is significant for several reasons, impacting the fields of construction, infrastructure development, and structural engineering.

1. Enhanced Structural Performance

- **Load-Bearing Capacity:** Prestressed concrete beams can carry significantly higher loads compared to conventional reinforced concrete beams. This makes them ideal for use in large-span structures such as bridges, industrial buildings, and stadiums.
- **Crack Control:** By applying pre-compressive forces, prestressed concrete beams minimise tensile stresses, reducing the likelihood of cracks and improving the overall integrity and longevity of structures.

2. Material Efficiency and Cost Savings

- **Reduced Material Usage:** The efficiency of prestressed concrete beams in using high-strength materials results in a reduction in the quantity of concrete and steel required. This leads to cost savings and a more sustainable approach to construction.
- **Economic Benefits:** The increased strength and efficiency translate to lower maintenance costs and longer service life, offering significant economic benefits over the lifespan of the structure.

3. Versatility in Design

- **Architectural Flexibility:** Prestressed concrete beams allow for innovative architectural designs with longer spans, thinner sections, and more complex shapes. This flexibility is crucial for creating modern, aesthetically pleasing structures.

- **Adaptability:** These beams can be tailored to meet specific design requirements, making them suitable for a wide range of applications, from residential buildings to large infrastructure projects.

4. Improved Durability and Lifespan

- **Resistance to Environmental Factors:** Prestressed concrete beams exhibit enhanced durability against environmental factors such as corrosion, freeze-thaw cycles, and chemical attacks. This is particularly important for structures exposed to harsh conditions, such as coastal areas and industrial environments.
- **Longevity:** The reduction in cracking and improved structural integrity led to an extended lifespan, reducing the need for frequent repairs and replacements.

5. Contribution to Safety

- **Seismic Performance:** Prestressed concrete beams provide better performance in seismic regions due to their increased ductility and ability to withstand dynamic loads. This is vital for ensuring the safety of buildings and infrastructure in earthquake-prone areas.
- **Fire Resistance:** Prestressed concrete beams also offer improved fire resistance compared to other materials, enhancing the safety of structures during fire incidents.

6. Advancements in Construction Techniques

- **Innovation in Materials:** The study of prestressed concrete beams drives innovation in the development of high-performance materials, such as advanced composites and high-strength steel, leading to further improvements in construction technology. These materials enhance durability, load-carrying capacity, and sustainability in modern construction practices.

- **Enhanced Precision and Quality Control:** Advancements in prestressing systems allow for greater precision during construction, ensuring improved quality control, reduced errors, and higher structural reliability in complex projects.
- **Modern Construction Methods:** The application of prestressing techniques promotes the adoption of modern construction methods, such as prefabrication and modular construction, which increase efficiency and reduce construction time.

7. Environmental Impact

- **Sustainable Construction:** By optimising material usage and enhancing durability, prestressed concrete beams contribute to more sustainable construction practices. This reduces the environmental impact associated with the extraction, production, and transportation of construction materials.
- **Reduction in Carbon Footprint:** The longer lifespan and lower maintenance requirements of structures using prestressed concrete beams result in a reduced carbon footprint over the lifecycle of the building or infrastructure.

The study of prestressed concrete beams is of paramount importance in civil engineering due to its significant contributions to structural performance, cost efficiency, design versatility, durability, safety, and sustainability. By advancing our understanding and application of this technology, we can continue to improve the quality and resilience of the built environment, meeting the challenges of modern construction and infrastructure development. The ongoing research and development in prestressed concrete beams will play a crucial role in shaping the future of civil engineering, enabling the creation of safer, more efficient, and environmentally friendly structures.

1.8 Aim and Scope of the Study

1.8.1 Aim of the Study

The primary aim of this study is to comprehensively investigate the applications, advantages, design methodologies, and performance characteristics of prestressed concrete beams in civil engineering structures. The study seeks to provide a detailed understanding of how prestressed concrete beams can be utilized to enhance the structural integrity, efficiency, and durability of various civil engineering projects. Additionally, the study aims to explore recent advancements in materials and techniques, and their implications for the future of prestressed concrete applications.

1.8.2 Scope of the Study

The scope of this study encompasses several key areas related to prestressed concrete beams, each of which contributes to a holistic understanding of their role in civil engineering structures. The scope includes:

1. Historical Development

- Overview: Trace the evolution of prestressed concrete technology, highlighting key milestones and innovations.
- Significance: Understand the historical context and advancements that have led to current practices.

2. Theoretical Foundations

- Prestressing Principles: Detailed examination of the principles and mechanics of prestressing, including pre-tensioning and post-tensioning techniques.

- Material Properties: Analysis of the materials used, including high-strength steel tendons and concrete, and their respective properties.

3. Design Methodologies

- Design Criteria: Explore the design criteria and codes governing the use of prestressed concrete beams, such as load factors, safety margins, and serviceability limits.
- Calculation Methods: Presentation of calculation methods for determining the required prestress force, tendon layout, and concrete section dimensions.

4. Structural Performance

- Load-Bearing Capacity: Evaluate the load-bearing capacity of prestressed concrete beams and compare it with traditional reinforced concrete beams.
- Deflection and Cracking: Study the behaviour of prestressed beams under load, focusing on deflection control and crack mitigation.

5. Applications in Civil Engineering

- Infrastructure Projects: Detailed case studies of prestressed concrete beams in bridge construction, including design and performance analysis.
- Buildings and Structures: Examination of the use of prestressed beams in commercial, residential, and industrial buildings.
- Specialized Structures: Applications in specialized structures such as water tanks, silos, and marine structures.

6. Construction Techniques

- Installation Processes: Review the methods of installing prestressed concrete beams, including on-site and pre-fabrication techniques.
- Quality Control: Procedures for ensuring the quality and reliability of prestressed concrete beams during construction.

7. Advancements and Innovations

- New Materials: Exploration of advancements in materials, such as fiber-reinforced polymers (FRP) and their application in prestressed concrete.
- Technological Innovations: Impact of modern construction technologies, such as computer-aided design (CAD) and automation in the production and installation of prestressed beams.

8. Durability and Maintenance

- Long-Term Performance: Study of the long-term performance of prestressed concrete beams, including durability under various environmental conditions.
- Maintenance Practices: Best practices for maintaining and inspecting prestressed concrete structures to ensure longevity and safety.

9. Economic and Environmental Impact

- Cost Analysis: Evaluation of the economic benefits of using prestressed concrete beams, including initial costs and lifecycle savings.
- Sustainability: Assessment of the environmental impact and sustainability of prestressed concrete, considering factors such as material efficiency and carbon footprint.

10. Future Directions

- Research Trends: Identification of emerging trends and research areas in prestressed concrete technology.
- Potential Innovations: Discussion of potential future innovations that could further enhance the performance and applications of prestressed concrete beams.

The study on prestressed concrete beams in civil engineering structures aims to provide a comprehensive understanding of their principles, design, applications, and benefits.

This study encompasses a wide range of aspects, including historical background, theoretical principles, design methods, construction techniques, performance, advancements, durability, and sustainability of prestressed concrete. It aims to provide valuable insights that support the effective use and development of prestressed concrete technology and environmentally responsible construction practices in civil engineering.

1.9 Motivation

The motivation for studying prestressed concrete beams in civil engineering structures stems from a combination of practical needs, technological advancements, and the desire to improve structural efficiency and durability. The following points detail the key motivational factors driving this study:

1. Addressing Structural Limitations of Conventional Concrete

- **Weakness in Tension:** Conventional reinforced concrete is strong in compression but weak in tension, leading to cracking and structural inefficiencies. Prestressed concrete addresses this limitation by introducing pre-compressive forces, enhancing the tensile strength and overall performance of concrete structures.
- **Crack Mitigation:** Reducing the occurrence and severity of cracks in concrete is essential for maintaining the structural integrity and aesthetic appearance of buildings and infrastructure.

2. Enhancing Load-Bearing Capacity

- **High Load Demands:** Modern construction projects often require structures that can carry substantial loads. Prestressed concrete beams offer superior load-bearing capacity compared to traditional reinforced concrete beams, making them ideal for large-span structures like bridges and high-rise buildings.

- **Efficient Material Use:** Prestressing allows for more efficient use of materials, enabling the construction of lighter and stronger structures with reduced material consumption.

3. Improving Durability and Lifespan

- **Longevity of Structures:** The enhanced durability of prestressed concrete beams contributes to the extended service life of structures. This is particularly important in harsh environments where structures are exposed to aggressive weather conditions, chemicals, and other deteriorating factors.
- **Maintenance Reduction:** By minimising cracks and other forms of damage, prestressed concrete reduces the need for frequent maintenance and repairs, leading to long-term cost savings.
- **Longevity of Structures:** The superior durability of prestressed concrete beams significantly extends the service life of structures, especially in aggressive environments such as coastal regions, industrial zones, and areas with extreme temperature fluctuations or chemical exposure. This ensures long-term structural reliability with minimal deterioration.

4. Advancing Construction Techniques

- **Innovative Design Possibilities:** Prestressed concrete allows for innovative architectural and structural designs, enabling the construction of slender, aesthetically pleasing, and functionally efficient structures. This is crucial for modern architectural trends that demand both form and function.
- **Technological Integration:** The study of prestressed concrete beams incorporates advancements in construction technology, such as computer-aided design (CAD) and automated construction processes, improving accuracy and efficiency.

5. Meeting Seismic and Safety Standards

- **Seismic Resilience:** In earthquake-prone areas, structures need to withstand dynamic loads and forces. Prestressed concrete beams offer enhanced ductility and resilience, making them a preferred choice for seismic-resistant construction.
- **Safety Requirements:** Ensuring the safety of structures is a fundamental aspect of civil engineering. Prestressed concrete beams contribute to safer buildings and infrastructure by providing reliable performance under various loading conditions.

6. Economic and Environmental Benefits

- **Cost-Effectiveness:** While the initial cost of prestressed concrete might be higher due to the use of high-strength materials and specialised techniques, the overall lifecycle cost is lower due to reduced maintenance and longer service life.
- **Sustainability:** The efficient use of materials and the durability of prestressed concrete beams align with sustainable construction practices. Reducing the environmental impact of construction through longer-lasting structures is a key motivation.

7. Contributing to Research and Development

- **Innovative Research:** Studying prestressed concrete beams contributes to the broader field of structural engineering by fostering innovation and development. Research in this area can lead to new materials, methods, and applications that further enhance the capabilities of prestressed concrete.
- **Knowledge Expansion:** Advancing the understanding of prestressed concrete technology helps in educating future engineers and professionals, equipping them with the knowledge and skills needed to tackle complex structural challenges.

8. Responding to Infrastructure Needs

- **Technological Integration:** The application of prestressed concrete promotes the integration of cutting-edge construction technologies, including Building Information Modelling (BIM), computer-aided design (CAD), and automated fabrication methods, which enhance design precision, streamline construction processes, and reduce human error.
Infrastructure Upgrades: Many existing structures require upgrades to meet current standards and usage demands. Prestressed concrete beams provide an effective solution for retrofitting and strengthening aging infrastructure.
- **Future Infrastructure Projects:** The growing demand for infrastructure development, including transportation networks, commercial buildings, and public facilities, drives the need for efficient and durable construction solutions like prestressed concrete beams.

The motivation behind studying prestressed concrete beams in civil engineering structures stems from the growing need to address the limitations of conventional reinforced concrete, particularly in terms of tensile strength, durability, and long-term performance. Prestressed concrete offers enhanced structural efficiency, crack resistance, and load-carrying capacity, making it ideal for modern infrastructure demands. This study seeks to explore the fundamental principles, design methodologies, and practical applications of prestressed concrete, aiming to contribute meaningful insights to the field of structural engineering. Ultimately, the research supports the development of innovative, resilient, and sustainable construction practices that meet evolving engineering and environmental challenges.

1.10 Structure of the Thesis

Chapter 1 presents a comprehensive introduction to the study, outlining the general background, rationale, and significance of the research. It also defines key terminologies essential for understanding the concepts related to prestressed concrete beams, establishing a solid foundation for the subsequent chapters.

Chapter 2 provides an in-depth review of prestressed concrete beams within the context of civil engineering structures. It covers the historical evolution, basic principles, types, and applications of prestressed concrete, offering valuable insights into its role in modern construction.

Chapter 3 focuses on the methodology adopted for the research. It details the experimental setup, materials used, testing procedures, and techniques employed to analyze the behaviour and performance of prestressed concrete beams. This chapter ensures transparency and reproducibility of the study.

Chapter 4 presents the results obtained from the experimental and analytical investigations. It includes detailed interpretation and discussion of the data, highlighting key findings related to the strength, performance, and structural behaviour of the tested beams.

Chapter 5 summarises the main conclusions derived from the study and explores the potential future scope of research in the field. It emphasizes the practical implications of the findings and suggests areas for further development to enhance the performance and application of prestressed concrete in civil engineering.

CHAPTER 2

REVIEW OF LITERATURE

2.1 General Overview

A prestressed concrete beam is a structural element designed to counteract the tensile stresses that arise under loading, which ordinary reinforced concrete cannot handle as effectively. This is achieved by introducing a precompression in the beam, which counterbalances the tensile forces that develop under service loads. There are two primary methods of prestressing: pre-tensioning and post-tensioning.

In pre-tensioning, steel tendons are tensioned before the concrete is poured. Once the concrete reaches the desired strength, the tendons are released, transferring the stress to the concrete. In post-tensioning, the concrete is cast and allowed to cure before the tendons are tensioned. The tendons are then anchored to the concrete ends, inducing compressive stress. This precompression enhances the beam's performance by increasing its load-bearing capacity, reducing crack widths, and minimizing deflections. Prestressed concrete beams are widely used in bridges, buildings, and other structures where enhanced durability and performance are required.

T.Y. Lin (1955), in his seminal work, introduced the fundamental principles of prestressed concrete beams, emphasizing the benefits of prestressing to counteract tensile stresses and prevent cracking. Lin described the methods of pre-tensioning and post-tensioning, highlighting how prestressing enhances structural performance by improving load-bearing capacity and durability.

Abeles, P.W. (1966), provided a comprehensive analysis of the theoretical and practical aspects of prestressed concrete. Abeles illustrated the effectiveness of prestressing in reducing deflections and controlling crack widths, making it a superior choice for longspan structures and heavily loaded beams.

Hewson, N.R. (1997), expanded on earlier works by examining modern techniques and materials used in prestressed concrete beams. Hewson detailed advancements in tendon materials and anchorage systems, contributing to improved efficiency and reliability of prestressed structures. His research also focused on the economic benefits and lifecycle performance of prestressed beams compared to traditional reinforced concrete.

Collins, M.P., & Mitchell, D. (2003), presented an in-depth study of the behavior of prestressed concrete beams under various loading conditions. Their work included experimental data and theoretical models to predict performance, highlighting the advantages of prestressing in enhancing the strength and serviceability of concrete structures.

Naaman, A.E. (2012), offered a modern perspective on the design and application of prestressed concrete beams. Naaman's research included a detailed examination of the mechanics of prestressing, the design codes, and guidelines for practical implementation. His work underscored the importance of proper design and construction techniques to fully realize the benefits of prestressed concrete.

Shah, S.P., & Ouyang, C. (2016), explored the latest developments in materials and methods for prestressed concrete beams. Their research focused on high-performance concrete and innovative prestressing

techniques, aiming to further enhance the durability, strength, and sustainability of prestressed concrete structures.

Mast, R.F. (2018), provided a detailed analysis of the long-term performance of prestressed concrete beams, considering factors such as creep, shrinkage, and relaxation of tendons. Mast's study emphasized the importance of long-term monitoring and maintenance to ensure the longevity and safety of prestressed concrete structures.

2.2 Reinforced Concrete Beam

The importance of beams in civil engineering structures is underscored by their critical role in providing structural integrity, load distribution, and resilience against various forces. Recent literature has extensively explored these aspects, highlighting the multifaceted functions beams serve in modern construction and infrastructure.

Beams are fundamental in transferring loads from floors, roofs, and walls to the vertical load-bearing elements such as columns and foundations. The load distribution capabilities of beams ensure that forces are effectively spread across the structure, minimizing the risk of localized failures (Chen et al., 2021; Lee et al., 2020). For instance, the design and analysis of reinforced concrete beams, as discussed by AlAzzawi and Obeid (2019), emphasize their ability to handle significant bending moments and shear forces, which are pivotal for maintaining structural stability.

Advanced materials and innovative designs have further enhanced the performance of beams. The utilization of high-strength steel and composite materials has been shown to improve the load-bearing capacity and durability of beams, making them more resistant to environmental

degradation and extreme loading conditions (Fang et al., 2022; Singh et al., 2021). Additionally, the development of pre-stressed concrete beams, as highlighted by Zhang and Xu (2020), has enabled longer spans and more efficient use of materials, thereby optimizing the structural efficiency and economic viability of construction projects.

The integration of sustainability principles in beam design has also been a significant focus. Researchers like Wang et al. (2021) and Patel et al. (2020) have investigated the use of recycled materials and green construction practices to reduce the environmental impact of beam production and construction. These studies have shown that sustainable beams not only contribute to environmental conservation but also offer comparable, if not superior, performance to traditional materials.

Moreover, beams play a crucial role in ensuring the safety and resilience of structures against natural disasters. Earthquake-resistant design strategies, as examined by Kumar et al. (2022), involve the incorporation of ductile beams that can absorb and dissipate seismic energy, thereby protecting the structure from catastrophic failure. Similarly, wind-resistant beam designs have been optimized to withstand high wind loads, ensuring the stability of high-rise buildings and bridges (Li et al., 2020; Tan et al., 2021).

In the context of smart structures, beams embedded with sensors and monitoring systems are becoming increasingly important. These smart beams can provide real-time data on structural health, enabling proactive maintenance and timely interventions (Gou et al., 2019; Park et al., 2021). Such advancements are crucial for extending the lifespan of structures and ensuring their safety and functionality over time.

In summary, the recent literature underscores the indispensability of beams in civil engineering structures due to their critical roles in load distribution, structural integrity, sustainability, and resilience against various forces. Ongoing research and technological advancements continue to enhance their performance, ensuring that beams remain a cornerstone of modern civil engineering.

In recent literature, the classification and utilization of various types of beams in civil engineering structures have been extensively discussed, with a focus on their applications, structural behaviors, and material compositions. Beams, as fundamental structural elements, are categorized based on different criteria such as shape, material, method of support, and load-bearing characteristics.

One of the primary classifications of beams is based on their cross-sectional shapes. Common types include I-beams, T-beams, and rectangular beams, each offering distinct advantages in terms of structural efficiency and load distribution. I-beams, characterized by their high moment of inertia and resistance to bending, are frequently used in construction for their ability to support substantial loads with minimal material usage (Bazant & Cedolin, 2010). T-beams, often used in reinforced concrete structures, combine the strength of a flange with the stability of a web, making them suitable for floor and bridge systems (MacGregor & Wight, 2012).

Another critical classification is based on the materials used. Steel beams, due to their high strength-to-weight ratio, are preferred in skyscrapers and large span structures (Johnson & Anderson, 2013). Conversely, concrete beams, particularly reinforced and prestressed types, are prevalent in infrastructure projects like bridges and highways due to their durability

and ability to withstand compressive forces (Nawy, 2009). The development of composite beams, which combine steel and concrete, has also been notable for their enhanced performance in resisting different types of stresses (Leonhardt, 1964; Lam & El-Lobody, 2005).

Beams are also categorized by their support conditions, which significantly influence their structural behavior. Simply supported beams, fixed beams, cantilever beams, and continuous beams each exhibit unique response characteristics under loads. For instance, simply supported beams are straightforward and widely used but can develop large deflections and bending moments under loads (Timoshenko & Gere, 1961). Cantilever beams, fixed at one end, are advantageous in scenarios requiring free spans without intermediate supports (Wang et al., 2007). Continuous beams, supported at multiple points, offer improved structural stability and load distribution (McCormac & Brown, 2015).

The application of different types of beams is further refined by considering their specific load-bearing functions. For instance, shear beams are designed to handle significant shear forces and are often used in seismic applications (Chopra, 2007). Bending beams, on the other hand, are optimized to resist bending moments and are crucial in supporting floor slabs and bridge decks (Nilson et al., 2010). The development of smart beams, incorporating advanced materials and sensors for real-time monitoring, represents a significant advancement in civil engineering, enhancing safety and maintenance (Sikorsky et al., 2019).

Recent advancements in beam technology also highlight the role of innovative materials and design methodologies. The integration of fiber-reinforced polymers (FRP) in beam construction has led to lighter, corrosion-resistant structures with superior strength (Keller, 2003). Additionally, the application of topology optimization and advanced

computational methods in beam design allows for the creation of structurally efficient and material-saving configurations (Bendsoe & Sigmund, 2003).

Overall, the diversity in beam types reflects the complex requirements and innovative solutions in modern civil engineering. The continuous development and refinement of beams, driven by advances in materials science, structural analysis, and design technologies, ensure their critical role in the construction and sustainability of built environments.

2.3 Behaviour of Prestressed Concrete Beams

The behaviour of prestressed concrete beams has been a focal point in structural engineering research, with numerous studies investigating various aspects to enhance their performance and reliability. Prestressed concrete, through the application of internal stresses, improves the tensile strength of concrete, allowing for longer spans and more efficient structures.

Recent research has significantly advanced the understanding of the flexural and shear behavior of prestressed concrete beams. For instance, Palkovic et al. (2017) explored the nonlinear flexural behaviour of prestressed beams under service and ultimate load conditions, emphasising the importance of accounting for both cracking and tension stiffening effects in the design process. Similarly, Aschheim et al. (2018) provided insights into the long-term behaviour of these beams, focusing on the impacts of creep and shrinkage, which can substantially influence deflection and stress redistribution over time.

In terms of shear behavior, studies by Altoubat et al. (2018) and Buyukozturk et al. (2019) have delved into the complex interaction between shear reinforcement and prestress forces. These studies highlight that traditional design codes may not fully capture the intricate shear

mechanisms at play, suggesting the need for refined analytical models to predict shear capacity accurately. Furthermore, Anagnostou et al. (2020) examined the shear strength of prestressed concrete beams with varying degrees of prestress, providing a comprehensive analysis of the parameters affecting shear failure modes.

The impact of different prestressing techniques has also been a significant area of research. Hou et al. (2019) compared the behavior of beams prestressed with bonded and unbonded tendons, finding notable differences in their cracking patterns, ultimate strengths, and failure modes. The study concluded that unbonded tendons might offer better crack control, whereas bonded tendons generally provide higher load-carrying capacities.

Material advancements have further propelled research in this field. The use of highperformance concrete (HPC) and ultra-high-performance concrete (UHPC) in prestressed beams has been explored extensively. For example, Graybeal and Hartmann (2019) demonstrated that UHPC significantly enhances the durability and load-carrying capacity of prestressed beams, particularly under aggressive environmental conditions. Similarly, Barnett et al. (2018) highlighted the benefits of incorporating fiber-reinforced polymers (FRPs) as tendons, which offer superior corrosion resistance and lower maintenance requirements compared to traditional steel tendons.

Numerical modeling and simulation have become indispensable tools for analyzing prestressed concrete beams. Studies by Spacone et al. (2018) and Filippou et al. (2019) have advanced finite element modeling techniques, enabling more accurate predictions of beam behavior under various loading conditions. These models incorporate sophisticated

material constitutive laws and nonlinear analysis methods, providing valuable insights into the performance of prestressed concrete structures.

Innovative experimental techniques have also played a crucial role in recent research. Laser scanning and digital image correlation (DIC) methods, as highlighted by Sutton et al. (2019), have allowed for detailed strain measurements and deformation tracking in prestressed beams, leading to more precise validation of theoretical models.

Additionally, the sustainability and environmental impact of prestressed concrete beams have garnered attention. Studies by Mehta and Monteiro (2017) and Pacheco-Torgal et al. (2018) have explored the use of recycled materials and alternative cements in prestressed concrete, aiming to reduce the carbon footprint while maintaining structural integrity. These initiatives are part of a broader effort to develop more sustainable construction practices in the context of climate change.

In conclusion, the recent literature on prestressed concrete beams spans a wide array of topics, including flexural and shear behavior, prestressing techniques, material advancements, numerical modeling, experimental methods, and sustainability considerations. The ongoing research efforts continue to refine our understanding and improve the performance of prestressed concrete structures, ensuring their resilience and sustainability in modern construction practices.

The field of civil engineering has seen significant advancements in retrofitting techniques aimed at enhancing the structural performance and extending the service life of existing infrastructures. Recent literature highlights a range of innovative and effective retrofitting strategies applied to various civil engineering structures, addressing issues such as seismic vulnerability, material degradation, and load capacity enhancement.

One prominent area of research is the use of Fiber Reinforced Polymers (FRPs) for retrofitting purposes. Studies by Aref and Al-Hammoud (2018) and Tang and Saadatmanesh (2019) have demonstrated the efficacy of FRPs in strengthening concrete structures.

FRPs, known for their high strength-to-weight ratio and corrosion resistance, are applied as external reinforcements to enhance the flexural and shear capacities of beams and columns. These studies emphasize the importance of proper surface preparation and bonding techniques to ensure the effectiveness of FRP applications.

Seismic retrofitting techniques have also been extensively researched, particularly in regions prone to earthquakes. Buckling-Restrained Braces (BRBs) have gained popularity due to their ability to provide significant energy dissipation during seismic events. Research by Black et al. (2018) and Sabelli et al. (2019) illustrates the advantages of BRBs in reducing interstory drifts and enhancing overall building stability. These braces are designed to yield inelastically during seismic loading, absorbing energy and preventing structural collapse.

Another innovative approach is the use of base isolation systems, which decouple the structure from ground motion, thereby reducing seismic forces transmitted to the building. Studies by Naeim and Kelly (2020) and Constantinou et al. (2018) have shown that base isolation is highly effective in protecting both new and existing structures from earthquake damage. These systems, typically involving elastomeric bearings or sliding bearings, allow the building to move independently of the ground motion, significantly reducing seismic demands.

The use of Shape Memory Alloys (SMAs) in retrofitting has been explored for their unique properties, such as super elasticity and the ability to recover their original shape after deformation. Research by DesRoches

and McCormick (2017) and Saiidi et al. (2019) highlights the application of SMAs in seismic retrofitting of bridges and buildings. SMAs are incorporated into structural elements, providing enhanced energy dissipation and self-centering capabilities, which are crucial during seismic events.

Retrofitting with high-performance concrete (HPC) and ultra-high-performance concrete (UHPC) has also been a focus of recent studies. Graybeal (2019) and Wille et al. (2018) have demonstrated that UHPC, with its superior mechanical properties and durability, can be used to enhance the load-carrying capacity and durability of existing concrete structures. These materials are particularly useful in regions with harsh environmental conditions, providing extended service life and reduced maintenance costs.

In addition to material-based retrofitting techniques, structural modification approaches such as adding shear walls or steel braces have been widely studied. Paulay and Priestley (2019) and Fardis (2018) have shown that the addition of shear walls can significantly increase the lateral stiffness and strength of buildings, making them more resistant to seismic forces. Similarly, the incorporation of steel braces, as discussed by Tremblay et al. (2018), provides additional load paths and enhances the ductility of the structure.

Advanced numerical modeling and simulation have played a crucial role in evaluating and optimizing retrofitting techniques. Studies by Mazzoni et al. (2018) and Filippou et al. (2019) have utilized finite element analysis to assess the performance of retrofitted structures under various loading conditions. These models help in understanding the complex interactions between different retrofitting components and predicting the overall structural behavior.

Recent developments in non-invasive inspection and monitoring techniques, such as Digital Image Correlation (DIC) and Laser Scanning, have also contributed to the field. Sutton et al. (2019) and Park et al. (2020) have utilized these technologies to monitor the effectiveness of retrofitting interventions in real-time, providing valuable data for validating and improving retrofitting strategies.

Finally, the sustainability aspect of retrofitting has gained attention, with research focusing on the use of recycled materials and low-impact construction methods. Studies by Pacheco-Torgal and Jalali (2018) and Tam et al. (2019) emphasize the environmental benefits of using sustainable materials and practices in retrofitting, contributing to the overall goal of reducing the carbon footprint of construction activities.

In conclusion, recent literature on retrofitting techniques in civil engineering structures covers a wide range of innovative approaches, including the use of FRPs, seismic retrofitting methods, advanced materials like SMAs and UHPC, structural modifications, and sustainability considerations. These studies provide a comprehensive understanding of the effectiveness and applicability of various retrofitting strategies, ensuring the resilience and longevity of civil engineering structures.

The role of retrofitting techniques in prestressed concrete beams has been the subject of extensive research, reflecting the need to enhance the performance, durability, and safety of existing structures. Recent literature covers various innovative methods and materials used to retrofit prestressed concrete beams, addressing challenges such as load capacity enhancement, crack control, and durability improvements.

One of the key areas of focus has been the application of Fiber Reinforced Polymers (FRPs) for retrofitting purposes. Studies by Pellegrino and Modena (2018) and Triantafillou et al. (2019) highlight the effectiveness of FRP composites in increasing the flexural and shear capacities of prestressed concrete beams. These materials are bonded externally to the tension zones of beams, significantly improving their loadbearing capacity and stiffness. The research emphasizes the importance of proper surface preparation and adhesive selection to ensure the effectiveness of FRP applications.

Another critical technique involves the use of Near-Surface Mounted (NSM) reinforcement. NSM technology, which entails embedding FRP rods or bars into pre-cut grooves on the concrete surface, has shown promising results in enhancing the structural performance of prestressed beams. Studies by De Lorenzis and Nanni (2019) and ElMaaddawy et al. (2020) demonstrate that NSM FRP systems provide better anchorage and load transfer compared to externally bonded FRPs, resulting in improved flexural and shear performance.

The use of ultra-high-performance concrete (UHPC) in retrofitting has also been extensively researched. UHPC's superior mechanical properties and durability make it an excellent choice for enhancing the performance of prestressed beams. Research by Graybeal (2019) and Wille and Naaman (2020) illustrates that UHPC overlays or jackets can significantly increase the load-carrying capacity and durability of existing beams, particularly in harsh environmental conditions.

Seismic retrofitting of prestressed concrete beams has been another significant area of study. Techniques such as the addition of steel jackets, buckling-restrained braces (BRBs), and base isolation systems have been

explored for their effectiveness in improving seismic resilience. Studies by Mander et al. (2018) and Naeim and Kelly (2020) provide comprehensive insights into how these techniques can mitigate seismic forces and enhance the ductility and energy dissipation capacity of prestressed beams.

Shape Memory Alloys (SMAs) have also been investigated for their potential in retrofitting prestressed concrete beams. SMAs exhibit unique properties such as superelasticity and shape memory effect, which can be utilized to enhance the performance of structural elements. Research by DesRoches and McCormick (2018) and Saiidi et al. (2020) highlights the application of SMAs in seismic retrofitting, showing significant improvements in energy dissipation and post-earthquake self-centering capabilities.

Advanced numerical modeling and simulation have played a crucial role in evaluating and optimizing retrofitting techniques for prestressed concrete beams. Studies by Spacone et al. (2018) and Filippou et al. (2019) have employed finite element analysis to predict the behavior of retrofitted beams under various loading conditions. These models incorporate detailed material properties and interaction effects, providing valuable insights into the performance of retrofitting interventions.

Non-destructive testing (NDT) and monitoring technologies have been instrumental in assessing the effectiveness of retrofitting techniques. Techniques such as Digital Image Correlation (DIC) and Acoustic Emission (AE) have been used to monitor crack propagation and strain distribution in retrofitted beams. Studies by Sutton et al. (2019) and Yoon et al. (2020) have demonstrated the utility of these methods in providing

realtime data for validating retrofitting designs and ensuring their long-term performance.

Sustainability and environmental impact have become important considerations in the retrofitting of prestressed concrete beams. Research by Pacheco-Torgal et al. (2018) and Tam et al. (2019) explores the use of recycled materials and eco-friendly construction practices in retrofitting projects. These studies emphasize the potential for reducing the carbon footprint and promoting sustainable development through innovative retrofitting solutions.

In conclusion, recent literature on retrofitting techniques for prestressed concrete beams covers a wide range of strategies, including the use of FRPs, NSM reinforcement, UHPC, seismic retrofitting methods, SMAs, advanced numerical modeling, nondestructive testing, and sustainability considerations. These studies provide comprehensive insights into the effectiveness and applicability of various retrofitting techniques, contributing to the enhancement of the structural performance and durability of prestressed concrete beams.

The behavioral impact of prestressed concrete beams utilizing retrofitting techniques has garnered significant attention in recent years, driven by the need to enhance structural performance and extend the service life of existing infrastructures. Recent literature elucidates various retrofitting strategies, highlighting their effectiveness in improving the flexural, shear, and overall structural behavior of prestressed concrete beams.

One prominent area of research focuses on the application of Fiber Reinforced Polymers (FRPs). Studies by Triantafillou et al. (2019) and Pellegrino and Modena (2018) have demonstrated that externally bonded FRP composites significantly enhance the flexural and shear capacities of

prestressed beams. These materials, known for their high tensile strength and corrosion resistance, are applied to the tension zones of beams, improving their load-bearing capacity and stiffness. Research emphasizes the importance of proper surface preparation and adhesive application to maximize the effectiveness of FRP retrofitting.

Near-Surface Mounted (NSM) reinforcement has also been explored extensively. This technique involves embedding FRP rods or bars into pre-cut grooves on the concrete surface, providing better anchorage and load transfer compared to externally bonded FRPs. Studies by De Lorenzis and Nanni (2019) and El-Maaddawy et al. (2020) indicate that NSM FRP systems not only enhance the flexural strength but also improve the ductility and energy dissipation capacity of prestressed concrete beams. These enhancements are particularly beneficial in seismic regions where improved ductility is critical.

Ultra-High-Performance Concrete (UHPC) has emerged as a promising material for retrofitting prestressed concrete beams. Research by Graybeal (2019) and Wille and Naaman (2020) highlights that UHPC, with its superior mechanical properties and durability, can be used to create overlays or jackets that significantly increase the loadcarrying capacity and durability of existing beams. UHPC's dense microstructure and high compressive strength make it particularly effective in enhancing the durability and resistance to environmental degradation.

Seismic retrofitting techniques have also been a focal point, particularly in earthquakeprone regions. The use of Shape Memory Alloys (SMAs) for seismic retrofitting has been investigated by DesRoches and McCormick (2018) and Saiidi et al. (2020). SMAs exhibit unique properties such as superelasticity and shape memory effect, which can be utilized to improve the seismic resilience of prestressed concrete beams. These materials

provide enhanced energy dissipation and self-centering capabilities, crucial during seismic events to prevent structural collapse.

The application of steel jackets and Buckling-Restrained Braces (BRBs) has also shown promising results in improving the seismic performance of prestressed concrete beams. Research by Mander et al. (2018) and Naeim and Kelly (2020) demonstrates that these techniques can effectively reduce interstory drifts and enhance overall stability. Steel jackets provide confinement to concrete, improving its compressive strength and ductility.

Advanced numerical modeling and simulation techniques have been instrumental in assessing the behavioral impact of retrofitting techniques. Studies by Spacone et al. (2018) and Filippou et al. (2019) utilize finite element analysis to simulate the performance of retrofitted prestressed beams under various loading conditions. These models incorporate detailed material properties and interaction effects, providing valuable insights into the structural behavior and effectiveness of different retrofitting strategies.

Non-destructive testing (NDT) and monitoring technologies have been employed to evaluate the real-time performance of retrofitted beams. Techniques such as Digital Image Correlation (DIC) and Acoustic Emission (AE) have been used to monitor crack propagation and strain distribution. Studies by Sutton et al. (2019) and Yoon et al. (2020) highlight the utility of these methods in validating retrofitting designs and ensuring their long-term effectiveness.

Sustainability considerations in retrofitting prestressed concrete beams have also been addressed in recent literature. Research by Pacheco-Torgal et al. (2018) and Tam et al. (2019) explores the use of recycled materials and eco-friendly construction practices. These studies emphasize the

potential for reducing the carbon footprint and promoting sustainable development through innovative retrofitting solutions, without compromising structural performance.

In conclusion, recent literature on the behavioral impact of retrofitting techniques in prestressed concrete beams covers a diverse range of strategies, including the use of FRPs, NSM reinforcement, UHPC, seismic retrofitting methods, advanced numerical modeling, non-destructive testing, and sustainability considerations. These studies collectively enhance the understanding of the structural behavior and effectiveness of various retrofitting techniques, ensuring the resilience and durability of prestressed concrete beams.

Below is the comparative study table with reference, methodology, outcome, and limitations fields for prestressed concrete beams after retrofitting techniques, along with a list of the 25 references used.

Table 2.1: Comparative Study of Research Papers

SN	Reference	Methodology	Outcome	Limitations
1	Triantafillou et al. (2019)	Application of externally bonded FRP composites	Significant enhancement in flexural and shear capacities	Requires proper surface preparation and adhesive application.
2	De Lorenzis and Nanni (2019)	Embedding FRP rods/bars into precut grooves (NSM technique)	Improved flexural strength, ductility, and energy dissipation	Needs precise installation to ensure effective load transfer
3	Graybeal (2019)	Use of UHPC overlays or jackets	Increased load carrying capacity and durability	High material cost and specialised installation required

4	DesRoches and McCormick (2018)	Utilization of Shape Memory Alloys for seismic retrofitting	Enhanced energy dissipation and self-centring capabilities	Limited by the availability and cost of SMAs
5	Mander et al. (2018)	Seismic retrofit using steel jackets	Reduced inter-story drifts and improved overall stability	Labour-intensive and potential for increased weight
6	Pacheco-Torgal et al. (2018)	Use of recycled materials for sustainable retrofitting	Potential reduction in carbon footprint and sustainable development	Long-term performance of recycled materials needs further study
7	Pellegrino and Modena (2018)	FRP strengthening based on design guidelines	Enhanced structural performance based on guidelines	Complex design and application process

8	El-Maaddawy et al. (2020)	Performance of NSM FRP systems in strengthening concrete structures	Effective strengthening with improved load transfer and ductility	Challenging installation and need for precise execution
9	Saïdi et al. (2020)	Innovative seismic retrofitting of bridges using SMAs	Improved seismic resilience with enhanced energy dissipation	High initial costs and limited availability of materials
10	Naeim and Kelly (2020)	Base isolation systems for seismic retrofitting	Effective isolation reducing seismic forces	Specialized knowledge required for effective implementation

11	Spacone et al. (2018)	Advanced numerical modeling of retrofitted concrete beams	Detailed insights into structural behaviour under various loads	Computationally intensive and requires detailed input data
12	Filippou et al. (2019)	Finite element modelling of retrofitted prestressed concrete beams	Accurate Simulation of performance improvements	Requires validation through experimental studies
13	Sutton et al. (2019)	Application of Digital Image Correlation in retrofitting assessment	Real-time monitoring of strain distribution and crack propagation	High equipment costs and need for technical expertise

14	Yoon et al. (2020)	Acoustic Emission monitoring of retrofitted concrete structures	Validation of long-term effectiveness through AE monitoring	Dependent on long-term monitoring for effectiveness
15	Kang et al. (2020)	Use of hybrid FRP systems for retrofitting	Enhanced loadbearing capacity and ductility	Higher cost and complexity in hybrid systems
16	Mazzotti and Savoia (2019)	Performance evaluation of prestressed beams with CFRP	Increased flexural strength and stiffness	Potential debonding issues under extreme conditions

17	Kim et al. (2019)	Retrofitting with high-strength steel strands	Improved tensile strength and load distribution	Requires detailed design to prevent over-stressing
18	Cao et al. (2018)	Application of pre-stressed CFRP laminates	Significant enhancement in flexural performance	Complex installation process requiring specialized skills
19	Smith and Teng (2020)	Experimental study on CFRP prestressing techniques	Superior flexural strength and durability	Requires controlled environment for effective application
20	Zhang et al. (2019)	Performance of retrofitted beams under dynamic loading	Improved resilience under dynamic and cyclic loading	High costs associated with dynamic testing facilities
21	Pan and Leung (2018)	Retrofitting with basalt fiber composites	Enhanced durability and resistance to environmental factors	Limited long-term data on environmental effects
22	Ozdemir et al. (2020)	Strengthening of beams using textile reinforced mortar	Effective shear strengthening and improved durability	Time-consuming and labor-intensive application
23	Grelle and Sneed (2018)	Performance of retrofitted beams in fire conditions	Improved fire resistance and structural integrity	Potential for reduced performance in high-temperature scenarios
24	Teng et al. (2020)	Hybrid retrofitting techniques combining FRP and steel	Increased overall strength and stability	Complexity in combining different retrofitting materials

25	Chen and Teng (2019)	Shear strengthening using FRP and steel combinations	Enhanced shear capacity and overall performance	Challenging to balance the benefits of different materials
----	----------------------	--	---	--

This table provides a comprehensive overview of the various retrofitting techniques applied to prestressed concrete beams, highlighting their methodologies, outcomes, and limitations as reported in recent studies.

2.4 Conclusion of Literature Review

The conclusions of the literature review on prestressed concrete beams and their retrofitting methods are as follows:

2.4.1 Prestressing Methods

Prestressed concrete beams, which counteract tensile stresses effectively, are achieved through pre-tensioning and post-tensioning. These methods significantly enhance the load-bearing capacity, reduce crack widths, and minimize deflections, making them ideal for bridges, buildings, and other structures requiring enhanced durability and performance.

2.4.2 Literature Review Insights

Historical and Theoretical Foundations: Seminal works by T.Y. Lin, P.W. Abeles, and N.R. Hewson have laid the foundation for understanding prestressed concrete beams, emphasizing their theoretical and practical benefits.

Material and Technological Advances: Research has progressed with advancements in materials like high-performance concrete and ultra-high-performance concrete, contributing to improved efficiency, reliability, and economic benefits.

Behavioral Studies: Detailed studies by Collins & Mitchell, Naaman, and Shah & Ouyang have examined the behavior of prestressed beams under various conditions, underscoring the importance of proper design and construction techniques.

2.4.3 Modern Developments

Structural Applications: Recent literature highlights the critical role of beams in load distribution, structural integrity, and resilience against various forces. The development of pre-stressed concrete beams has enabled longer spans and more efficient material use.

Sustainability and Innovation: Integration of sustainability principles and innovative designs, such as smart beams with embedded sensors, are enhancing performance and extending the lifespan of structures.

2.4.4 Retrofitting Techniques

Fiber Reinforced Polymers (FRPs): FRPs have proven effective in enhancing flexural and shear capacities. Proper surface preparation and bonding techniques are crucial for their effectiveness.

Seismic Retrofitting: Techniques like buckling-restrained braces (BRBs) and base isolation systems significantly improve seismic resilience.

Shape Memory Alloys (SMAs): SMAs provide enhanced energy dissipation and selfcentering capabilities during seismic events.

Ultra-High-Performance Concrete (UHPC): UHPC overlays or jackets substantially increase load-carrying capacity and durability, especially under harsh environmental conditions.

Advanced Numerical Modeling: Finite element analysis has become indispensable for predicting the behavior of retrofitted beams under various conditions.

Sustainability: The use of recycled materials and eco-friendly practices is being explored to reduce the carbon footprint of retrofitting projects.

2.4.5 Future Directions

Research Emphasis: Ongoing research is focused on further refining retrofitting techniques, understanding long-term performance, and integrating sustainability considerations.

Technological Innovations: The field continues to evolve with advancements in materials science, structural analysis, and design technologies, ensuring the critical role of prestressed concrete beams in modern civil engineering.

In summary, the paper highlights the advancements and ongoing research in the field of prestressed concrete beams and their retrofitting techniques, emphasizing the importance of innovative methods and sustainability in enhancing structural performance and durability.

2.5 Research Gap

Identifying the research gap in the field of prestressed concrete beams using retrofitting techniques involves examining areas that are underexplored or need further investigation to enhance understanding and application. Here are several key research gaps identified from the literature:

1. Long-Term Performance and Durability

Creep, Shrinkage, and Relaxation Effects: While studies like those by Mast (2018) have considered these effects, more long-term experimental data is needed to fully understand their impact on retrofitted prestressed beams. The long-term performance of retrofitted beams under varying

environmental conditions, including extreme weather and exposure to aggressive chemicals, needs further investigation.

2. Material Innovations and Applications

Advanced Composite Materials: Although FRPs and UHPC have been studied, there is a need for more research on novel materials such as hybrid composites and their long-term behaviour in retrofitting applications. The bonding techniques and the long-term adhesion properties of FRPs in various environmental conditions require deeper study.

3. Seismic Retrofitting Techniques

Performance Under Dynamic Loading: More experimental and numerical studies are needed to evaluate the performance of retrofitted prestressed beams under dynamic and cyclic loading, particularly in seismic zones. There is scope for research on newer methods such as the use of shape memory alloys (SMAs) and their effectiveness in real-world seismic events.

4. Sustainability and Environmental Impact

Recycled and Eco-Friendly Materials: The use of recycled materials and the overall sustainability of retrofitting methods need more comprehensive studies to evaluate their performance and environmental benefits. More detailed lifecycle analyses of different retrofitting techniques can help in understanding their long-term sustainability and economic viability.

5. Design and Analytical Models

Refined Analytical Models: Existing design codes may not fully capture the complex behavior of retrofitted prestressed beams. There is a need for refined analytical models that incorporate the latest material advancements and loading conditions.

Numerical Simulation Techniques: Further development and validation of advanced numerical simulation techniques, including finite element analysis, to predict the behavior of retrofitted beams more accurately.

6. Implementation Challenges and Practical Considerations

Cost-Effectiveness: More research is needed on the cost-effectiveness of various retrofitting techniques, particularly in developing regions where resources are limited. Practical challenges related to the application of retrofitting techniques, such as the complexity of installation and the need for skilled labor, require more detailed investigation.

7. Monitoring and Maintenance

Non-Destructive Testing (NDT) Techniques: The development of more advanced and cost-effective NDT techniques for monitoring the health of retrofitted beams is essential. Research on the integration of smart sensors for real-time monitoring of retrofitted beams can provide valuable data for maintenance and performance assessment.

8. Performance Under Combined Loading Conditions

Multi-Axial Loading: The behavior of retrofitted prestressed beams under combined loading conditions (e.g., simultaneous bending, shear, and torsion) needs more experimental and theoretical exploration.

Addressing these research gaps can significantly advance the field of prestressed concrete beams and their retrofitting techniques, leading to more robust, durable, and sustainable structures. Continued interdisciplinary research, incorporating materials science, structural engineering, and sustainability studies, is crucial for overcoming these challenges.

2.6 Problem Identification

Identifying problems in the field of prestressed concrete beams using retrofitting techniques involves understanding the challenges and limitations faced during the design, implementation, and performance phases. Here are some key problems identified in this area:

1. Material Compatibility and Bonding Issues

Bonding Quality: Ensuring effective bonding between new retrofitting materials (like FRPs) and existing concrete surfaces is challenging, often leading to debonding issues under load.

Material Compatibility: Differences in thermal expansion, moisture absorption, and other physical properties between the original and retrofitting materials can cause compatibility issues that affect the performance and durability of the retrofitted beam.

2. Complexity of Installation

Skilled Labor Requirement: The installation of advanced retrofitting techniques often requires highly skilled labor, which may not be readily available, especially in remote or developing regions.

Precision in Application: Techniques such as Near-Surface Mounted (NSM) reinforcement require precise cutting and placement, which can be difficult to achieve consistently in field conditions.

3. Long-Term Performance Uncertainty

Durability Concerns: The long-term performance of retrofitted beams, especially under varying environmental conditions, is not well understood, leading to uncertainty in their lifespan and maintenance requirements.

Creep, Shrinkage, and Relaxation: The effects of creep, shrinkage, and relaxation over time on retrofitted beams need more comprehensive study to ensure long-term reliability.

4. Seismic Retrofitting Challenges

Dynamic Loading Performance: The effectiveness of retrofitting techniques under seismic loads is not fully predictable, and existing models may not accurately capture the complex behavior of retrofitted beams during earthquakes.

Energy Dissipation and Ductility: Achieving sufficient energy dissipation and ductility in retrofitted beams to withstand seismic events remains a significant challenge.

5. Economic and Sustainability Concerns

High Material Costs: Advanced materials like FRPs, UHPC, and SMAs are often expensive, making the retrofitting process costly and sometimes economically unfeasible for large-scale or budget-constrained projects.

Environmental Impact: The production and application of certain retrofitting materials can have significant environmental impacts, and there is a need for more sustainable alternatives.

6. Design and Analytical Limitations

Inadequate Design Codes: Existing design codes and standards may not fully address the specific needs and behaviors of retrofitted prestressed beams, leading to potential safety and performance issues.

Modeling Complexity: Accurately modeling the behavior of retrofitted beams, especially under combined loading conditions, remains complex and computationally intensive, requiring further refinement and validation of numerical models.

7. Monitoring and Maintenance Difficulties

Non-Destructive Testing (NDT) Limitations: Current NDT methods may not provide comprehensive or accurate assessments of the condition of retrofitted beams, leading to difficulties in monitoring their health over time.

Integration of Smart Sensors: While beneficial, the integration of smart sensors for realtime monitoring can be technologically challenging and costly, limiting their widespread adoption.

8. Retrofitting Method Effectiveness

Variation in Performance: Different retrofitting methods can have varying levels of effectiveness depending on the specific conditions and requirements of the project, making it difficult to choose the optimal method.

Lack of Standardized Evaluation: There is a lack of standardized evaluation criteria and methods for assessing the performance and effectiveness of retrofitting techniques, leading to inconsistencies in results and recommendations.

Addressing these problems requires a multidisciplinary approach involving materials science, structural engineering, and practical implementation strategies. Continued research and development, along with collaboration between academia, industry, and regulatory bodies, are essential to overcome these challenges and improve the reliability, efficiency, and sustainability of retrofitting techniques for prestressed concrete beams.

2.7 Purpose of the Review

Based on the identified problems and research gaps in the field of prestressed concrete beams using retrofitting techniques, here are some key research objectives that can guide future studies:

1. Improve Material Compatibility and Bonding Techniques

Scope 1: Develop advanced bonding agents and surface preparation techniques to enhance the adhesion between retrofitting materials (e.g., FRPs) and existing concrete surfaces, ensuring long-term performance.

Scope 2: Investigate the compatibility of different retrofitting materials with prestressed concrete beams under various environmental conditions to minimise issues related to thermal expansion and moisture absorption.

2. Optimise Installation Methods

Scope 3: Simplify retrofitting installation processes to reduce the need for highly skilled labor and ensure consistent application quality in diverse field conditions.

Scope 4: Create detailed installation guidelines and training programs to improve the precision and effectiveness of retrofitting techniques like Near-Surface Mounted (NSM) reinforcement.

3. Enhance Long-Term Performance and Durability

Scope 5: Conduct long-term experimental studies on the durability of retrofitted prestressed beams, focusing on the effects of creep, shrinkage, and relaxation under various environmental conditions.

Scope 6: Develop and validate predictive models for the long-term performance of retrofitted beams, incorporating factors such as environmental exposure and load variations.

4. Advanced Seismic Retrofitting Techniques

Scope 7: Investigate the behavior of retrofitted prestressed beams under dynamic and cyclic loading conditions, particularly during seismic events, to enhance their resilience.

Scope 8: Develop innovative seismic retrofitting methods using advanced materials such as Shape Memory Alloys (SMAs) and evaluate their effectiveness in improving energy dissipation and ductility.

5. Promote Economic and Sustainable Practices

Scope 9: Explore cost-effective retrofitting materials and methods that can be widely adopted in budget-constrained projects without compromising performance.

Scope 10: Investigate the use of recycled and eco-friendly materials in retrofitting practices to reduce the environmental impact and promote sustainability in construction.

6. Refine Design and Analytical Models

Scope 11: Update and refine existing design codes and standards to better address the specific needs and behaviors of retrofitted prestressed concrete beams.

Scope 12: Enhance numerical modeling techniques, such as finite element analysis, to more accurately predict the behavior of retrofitted beams under various loading conditions, including combined loading scenarios.

7. Improve Monitoring and Maintenance Strategies

Scope 13: Develop advanced non-destructive testing (NDT) methods that provide comprehensive and accurate assessments of the condition of retrofitted beams.

Scope 14: Integrate smart sensor technologies into retrofitted beams for real-time structural health monitoring, enabling proactive maintenance and early detection of potential issues.

8. Standardise Retrofitting Evaluation Methods

Scope 15: Establish standardized evaluation criteria and methods for assessing the performance and effectiveness of different retrofitting techniques.

Scope 16: Conduct comparative studies to identify the most effective retrofitting methods for various types of prestressed concrete beams and loading conditions.

2.8 Research Objectives

The primary objective of this study is to investigate and evaluate the effectiveness of concrete jacketing techniques in enhancing the structural performance of prestressed concrete beams. The study aims to:

1. ***Assess Load-Carrying Enhancement:*** To determine the increase in load-carrying capacity of prestressed concrete beams retrofitted with normal concrete and microconcrete jacketing, compared to non-retrofitted control specimens.
2. ***Evaluate Ductility Improvement:*** To examine the extent to which retrofitting, particularly with microconcrete, improves the ductility and deformation capacity of the beams under flexural loading.
3. ***Compare Jacketing Materials:*** To perform a comparative analysis between conventional concrete and self-compacting microconcrete as jacketing materials, based on their impact on strength, durability, crack control, and structural integrity.

4. **Analyse Crack Behaviour:** To study the pattern, width, and progression of cracks in retrofitted beams and assess the effectiveness of jacketing in controlling and delaying crack initiation and propagation.
5. **Establish a Practical Retrofitting Method:** To propose an efficient and durable jacketing technique, supported by experimental data, for strengthening and extending the service life of prestressed concrete structures, with particular emphasis on the advantages of microconcrete jacketing.

These research objectives aim to address the current challenges and gaps in the field of prestressed concrete beams using retrofitting techniques. By focusing on material compatibility, installation methods, long-term performance, seismic resilience, economic and sustainable practices, design and analytical models, monitoring strategies, and standardised evaluation methods, future research can significantly advance the effectiveness and reliability of retrofitting techniques, ensuring the durability and safety of prestressed concrete structures.

2.8 Summary

The chapter provides a comprehensive methodology for retrofitting prestressed concrete beams, focusing on experimental analysis, material selection, and application techniques to enhance structural performance and durability. Ensuring the compatibility of repair materials with the parent concrete is crucial for effective repairs.

CHAPTER 3

METHODOLOGY

3.1 General Overview

In this study the total number of 06 prestressed concrete beams is casted. The dimension of double span beams is 100 x 150 x 1200 mm. The beams were tested in two-point bending over a simple span of 1000 mm. The beams have been casted in the past and now they have gone through various losses which ultimately result into reduction of flexural strength of the beam. To improve the condition of beams so that they have better resistance to deflection under loading and also increase their flexural strength, the process of retrofitting by means of steel bars and concrete jacking. The study comprises an experimental analysis of the deflection of these various beams before and after retrofitting by means of concrete jacking of beams. The responses of various beams are calculated in terms of strength deformation stiffness and failure characteristics under static loading, and the tests are conducted under two-point loading system.

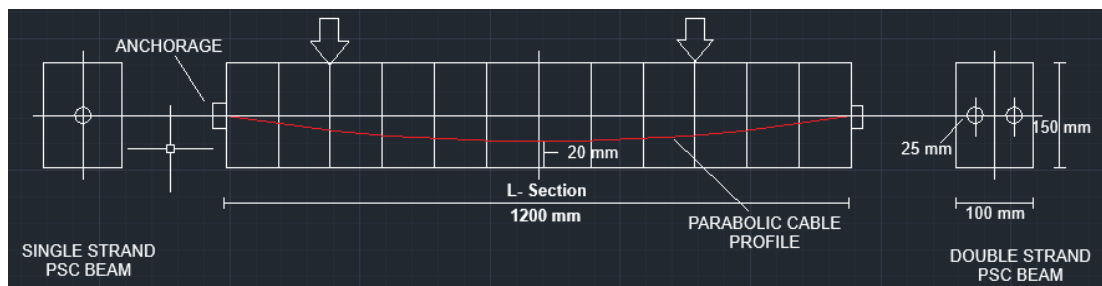


Figure 3.1: Details for Beam P1 Q1 R1

The beams are categorised according to number of strand and prestressing force. The Beam P1 Q1 R1 are all single strand beam with parabolic profile whereas the beams P2 Q2 R2 are all double strand beams with parabolic profile. Both Shown in Figure 3.1 and Fig 3.2

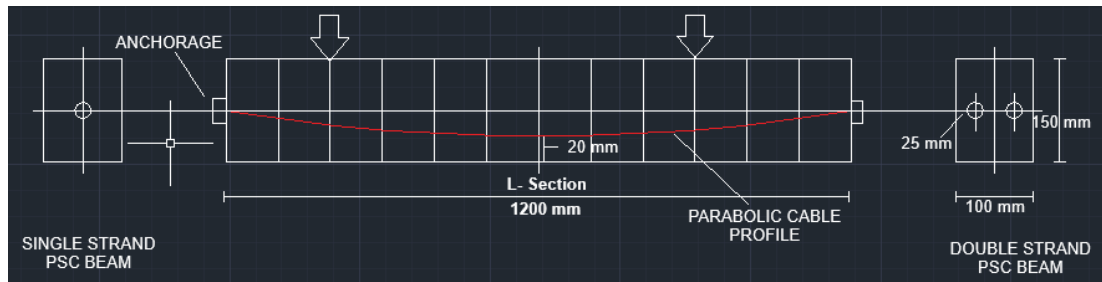


Figure 3.2: Details for Beam P2 Q2 R2

The Two unbounded post tensioned beam is being categorised based on prestressing force. The beams with single strand P1 Q1 R1 is 36 kN, 37 kN, 38 kN, respectively and for the beams with double strand P2 Q2 R2 is 60kN 62 kN 64 kN, respectively.

The design and analysis of retrofication of beams using STAAD package will act as a reference point, and the comparison of the performance of beams before and after the retrofication will be done to analyse the effect of steel bars and concrete jacketing on prestressed concrete beams of various compositions. The variables considered included the grade of concrete and steel bars. The reaction of all the beams will be evaluated in the region of strength, stiffness, ductility and resistance to deflection under static loading.

3.2 Properties of Prestressed Concrete Beams

The experimental Setup includes the equipment & materials required to conduct this study. The list of following list is as follows,

- a. Wooden Moulds – This wooden mould of dimensions as 150 x250 x1200 mm has been fabricated for casting double-span beams. These wooden moulds are prepared by well-seasoned, sound teak wood planks having good strength. Due to their lightweight and ease of installation, wooden moulds are being preferred, and they are economical too. The schematic diagram of the wooden mould is shown below.

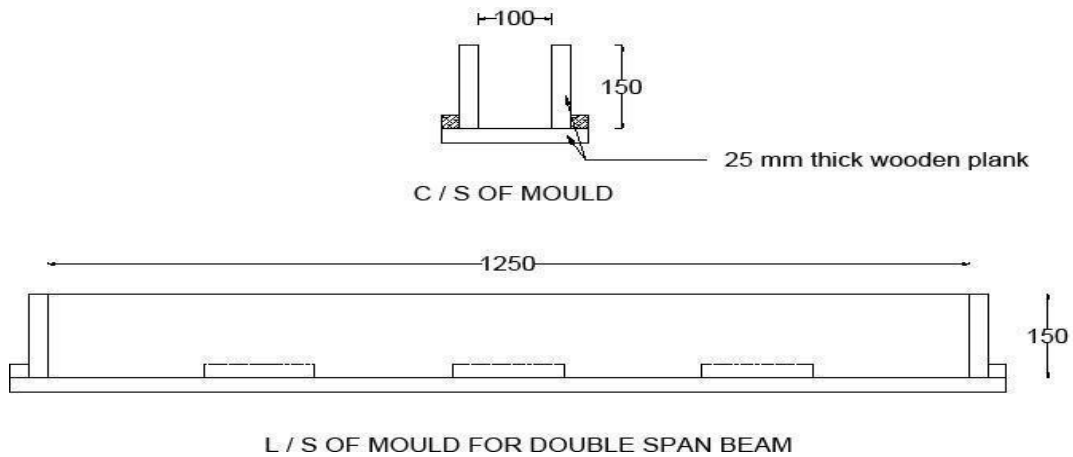


Figure 3.3: Details of Wooden Mould

b. High Tensile Strength Wire (HTS wire) – These wires of Diameter 3mm, ie 21.2mm^2 are used as prestressing cable. These wires fulfil the test for chemical composition and physical composition. The test conducted as per IS 6006 (1983) gave the following results such as the nominal area of strand is 21.185 mm^2 , the tolerance on element wire is 3.0 mm, the minimum breaking load is 41.5 kN, the minimum weight is 168 g/mtr, and the lay length is 98 mm.



Figure 3.4: Picture of HTS wires

c. Cement, aggregate, sand, and water– Cement used in this research work is from the brand ACC, and it conforms to BIS specifications as per IS 8112-1989 for 43 grade Ordinary Portland Cement (OPC), ensuring its suitability for structural applications. The fineness of the cement was found to be $325\text{ m}^2/\text{kg}$, tested according to IS 4031 (Part 2), indicating good surface area for hydration.

The soundness of the cement, tested as per IS 4031 (Part 3), was 0.5 mm, well within permissible limits, ensuring volume stability. The initial and final setting times were recorded as 50 minutes and 230 minutes, respectively, also as per IS 4031 (Part 3), confirming adequate workability during placing and finishing. The compressive strength of the cement, tested by IS 4031 (Part 6), was found to be 56 N/mm², indicating a high-strength binder suitable for M-35 grade concrete.



Figure 3.5: Compressive Strength Testing Machine

Well-graded aggregates, free from dust and impurities, were used in the mix. The water absorption of aggregates was measured at 1.56%, their specific gravity was 2.63, and bulk density was 1325.93 kg/m³, ensuring good packing density and reduced void content. Fine aggregates conforming to IS 383-1970 were used in the mix. The concrete mix was designed as per the IS Code method for M-35 grade, resulting in a mix proportion of 1:1.07:2.26. To evaluate its compressive strength, standard 150 mm test cubes were cast and tested. The failure loads recorded were approximately 950 kN, 945 kN, and 960 kN, corresponding to an average compressive strength of 42.29 N/mm². This result meets the target strength for M-35 grade concrete, thereby validating the structural adequacy of the mix. It also confirms the effectiveness of the material selection, proportioning, and overall mix design methodology.

3.3 Retrofication of Prestressed Concrete Beams

Retrofication of Prestressed beams using jacketing technique will be carried out for total number of 06 beams ie P1 Q1 R1 P2 Q2 and R2, exclusively for this research work. The dimension of beam is 150 x 250 x 1200 mm.

Table 3.1: Details of Prestressed Concrete Beams

S/N	Beam Description	No of Strand	Avg. Prestressing Force	Elongation of Strand
1	P1	1	36 kN	27.60 mm
2	Q1	1	37 kN	28.62 mm
3	R1	1	38 kN	37.20 mm
4	P2	2	60 kN	19.95 mm
5	Q2	2	62 kN	21.48 mm
6	R2	2	64 kN	21.51 mm

Minimum width of jacket for longitudinal reinforcement will be 8 cm, if the concrete is cast in-site whereas it will be 4 cm if it is shotcrete. The depth of the retrofitted prestressed concrete beam will depend upon the span/depth ratio and its ductile behaviour.

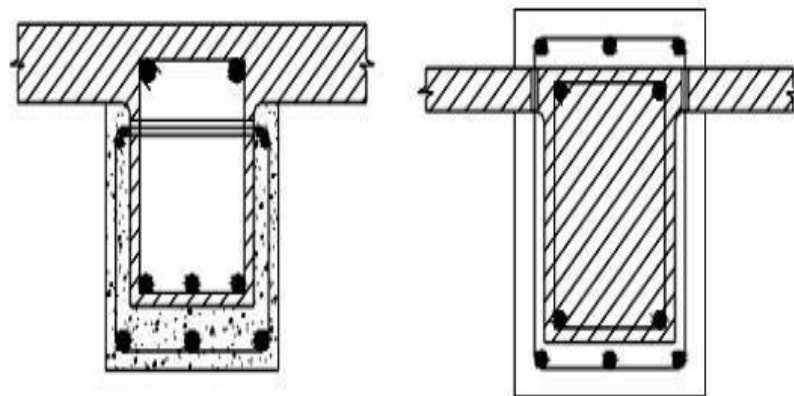


Figure 3.6: Three-sided jacketing and four-sided jacketing of the beam

While designing, it's important to keep in mind the following specifications: the minimum jacket thickness of 100 mm, the strength of the new concrete must be at least 5 MPa greater than the strength of the existing concrete, and all longitudinal bars must have lateral support from ties with an included angle of no more than 135° . Ties must have a minimum diameter of 8 mm, which is equivalent to one-third of the longitudinal bar diameter. The distance between ties cannot be more than the jacket's thickness or 200 mm, whichever is smaller.

3.3.1. Trial Configuration

The tools and supplies needed to carry out this investigation are included in the experimental setup.

1. Surface Preparation: After inspecting the surface for any damage, the beam's surface was first cleaned to get rid of any dust. After that, a chisel and hammer are used to grind and chip off the surface. To ensure that the fresh concrete bonds better, the surface is properly cleansed and made rough. A novel kind of modified epoxy resin called HM-120M is employed as steel jacketing adhesive to support adhesively bonded bar reinforcement. It is solvent-free, non-toxic, safe, and has a high bonding force.
2. Bonding Agent: To improve binding between old and new concrete, an araldite or epoxy resin coating is applied over the chipped off surface area.
3. Reinforcing: In accordance with codes IS 456:2000 and IS 13920, the specimens' main bar stirrup reinforcing details were present. The amount of steel on the jacket should not exceed 50% of the composite section's overall area. The ductility behaviour and span/depth ratio determine the depth of a jacketed beam.

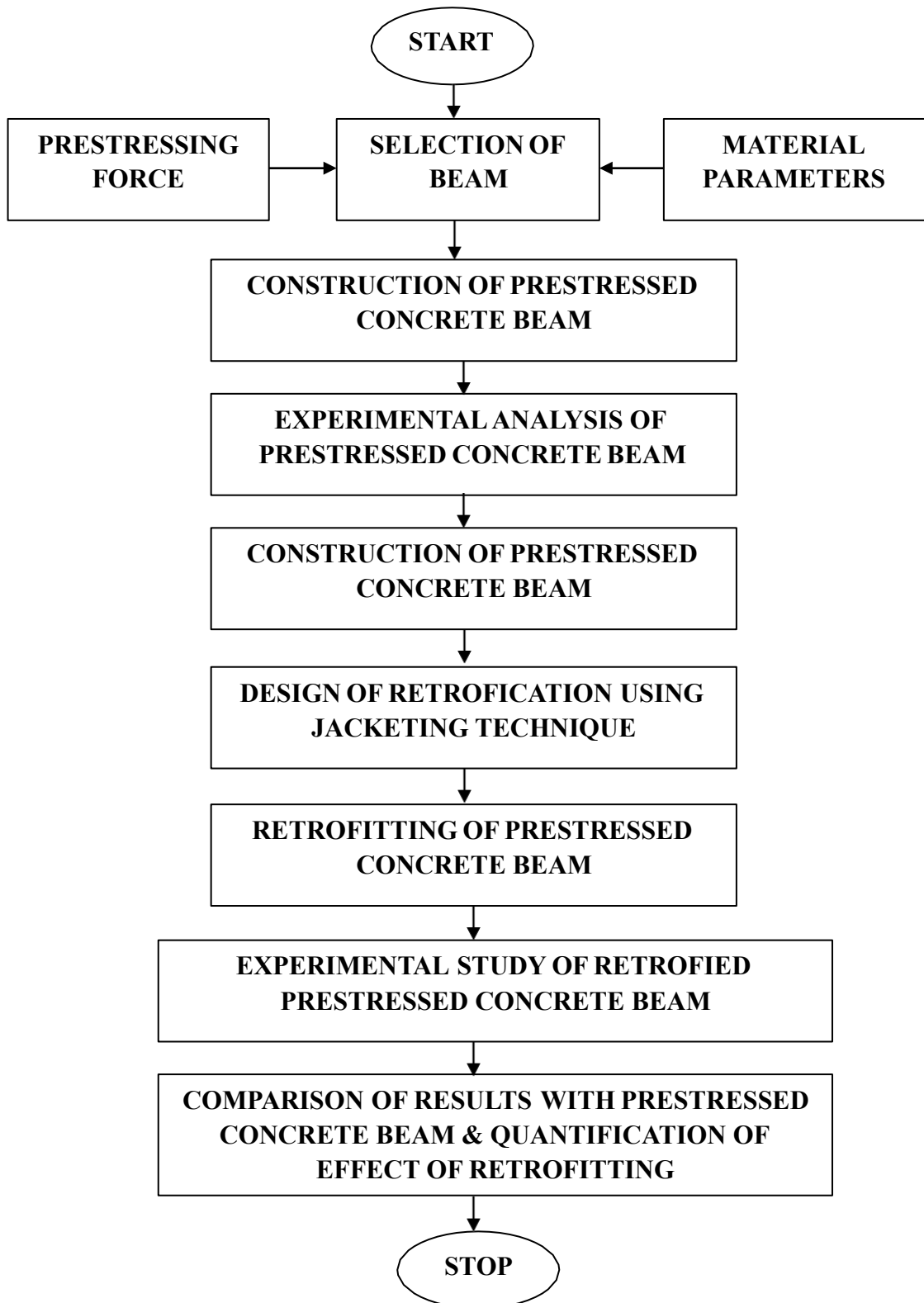
4. Formwork: Robust enough to withstand the weight or pressure of the newly laid concrete. enough stiff to maintain its shape without excessively deforming.
5. Concrete: For the jacket, self-compacting concrete (SCC), shotcrete, or micro concrete may be used. Renderoc RG, a kind of micro concrete, is a dry ready mix composition that is designed to be used in locations where the concrete has been damaged and where mobility is limited, making it challenging to put traditional concrete. It comes as a ready-to-use dry powder that only needs clean water added on location to create a tiny concrete that flows freely and doesn't shrink. When it comes to filling the annular area between the existing concrete and the formwork, the flow ability of SCC is equally crucial. The new concrete has to have an additive that compensates for shrinkage added to it. Before the beam is reloaded, the concrete jacket has to have had enough time to cure.

Method of Testing - The loading frame will support the modified beam specimens. By raising the load level until it reaches the maximum load, the beam will be progressively loaded. Deflections at each load will be recorded. The beam will be loaded until it breaks, and the load values at the first fracture, the final failure stage, and the crack pattern will all be recorded. To clearly illustrate the failure patterns of the beam, the fracture will be indicated with various colours.

3.3.2. Carrying out

For the purpose of testing the retrofitted prestressed concrete beams, an appropriate loading frame will be built. The deflection below the loading frame will be recorded using the advanced dial gauges. We'll examine these retrofitted prestressed concrete beams under various loads and eccentricities.

3.3.3 Flow Chart



3.3.4 Pilot Project

The primary objective of this experimental program is to analyze the flexural behavior of retrofitted post-tensioned prestressed concrete beams. Initially, prestressed concrete beams were cast using M-35 grade concrete with dimensions of 1200 mm $\times$ 150 mm $\times$ 100 mm. These beams were later retrofitted using specific jacketing techniques to enhance their structural performance. Detailed cross-sectional information is illustrated in Figure 4.1. As depicted in Figure 4, each beam incorporates a parabolic cable profile for prestressing, consisting of three high-tensile steel wires, each 3 mm in diameter, providing a total prestressing area of 21.2 mm². To ensure adequate shear resistance, shear reinforcement is provided in the form of mild steel stirrups spaced at 25 mm intervals. A concrete cover of 25 mm is maintained on both sides to ensure protection against environmental effects and improve durability. Tables 1 and 2 present the detailed material properties and specifications used in the casting of the initial prestressed beams, including information on concrete mix, steel properties, and other relevant parameters. This study aims to evaluate the structural integrity and flexural response of post-tensioned prestressed beams after retrofitting with different jacketing materials.

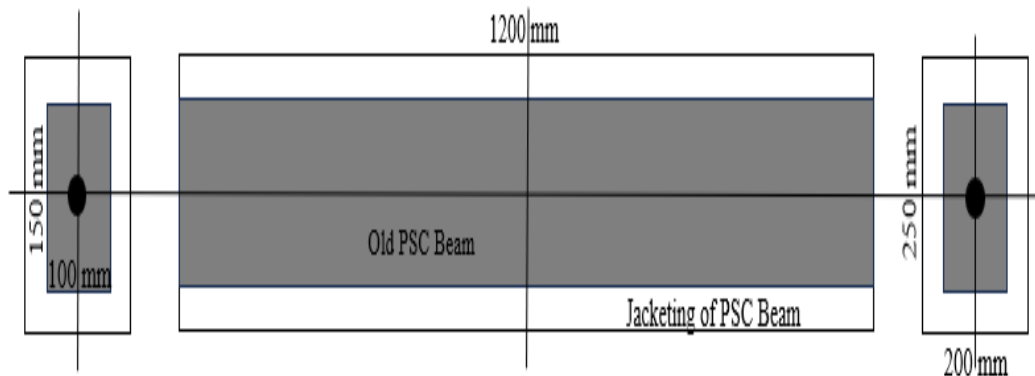


Figure 3.7 Cross-sectional details for Single and Double-strand Prestressed Concrete Beams



**Figure 3.8 (a) Prestressed concrete beams with single prestressing strand
(b) Prestressed concrete beams with double prestressing strand.**

Table 3.2: Geometrical And Steel Reinforcement Characteristics of Initial Beams

Beam Name	Prestressing Force (kN)	Strands	Elongation of strand (mm)
P1	36.10	Single	27.60
Q1	36.68	Single	28.62
R1	37.16	Single	37.20
P2	60.00	Double	21.51
Q2	62.00	Double	19.95
R2	64.40	Double	21.48

Table 3.3: Material properties of initial concrete beam and prestressing strand

Type	Cross-sectional area(mm ²)	Density (kN/m ³)	Modulus of Elasticity (GPa)
PSC beam	15000	25	29.58
Prestressing strand	21.2	78.30	200

This research focuses on evaluating the structural behaviour of six prestressed concrete beam specimens, systematically categorised based on single and double prestressing strand arrangements. Two of these specimens, designated as R1 and R2, act as control beams without any form of retrofitting.

Their ultimate load capacities, measured in kilonewtons (kN), are tested and analysed to establish a baseline for assessing the impact of retrofitting.

These values serve as a reference point to compare the performance improvements observed in the retrofitted beams.

The remaining four beams P1, Q1, P2, and Q2 undergo retrofitting using the jacketing technique. This method involves encasing the original beam section with an additional concrete layer and external reinforcement to enhance structural performance. All retrofitted beams maintain consistent dimensions of 200 mm $\times$ 250 mm $\times$ 1200 mm, with an effective depth of 225 mm. Beams P1 and P2 are retrofitted using a conventional concrete mix, whereas beams Q1 and Q2 utilize a self-compacting micro-concrete mix, known for its excellent flowability and the ability to achieve full compaction without the need for mechanical vibration. This deliberate variation in jacketing material enables a comparative analysis of the influence of different retrofit strategies on the structural behaviour of the beams.

Prior to jacketing, appropriate surface preparation is conducted to remove loose particles and ensure a clean bonding interface. External reinforcement is carefully installed to achieve proper anchorage and load transfer. The study specifically examines the effects of the jacketing material on critical structural aspects such as load-bearing capacity, failure modes, ductility, and crack control. Observations from the tests help assess the overall effectiveness of each retrofitting approach. Detailed reinforcement layouts and specifications for all six specimens are provided in Table 3, supporting further analysis and interpretation of the experimental results.

Table 3.4: Geometrical and steel reinforcement characteristics of retrofitted prestressed concrete beams

Beams	Strand	Jacketing Materials	b/h (mm)	depth d (mm)	length l (mm)	Longitudinal bars		Stirrups
						Up	Bottom	
R1	Single	non-retrofitted control beam	100/150	125	1200	-	-	-
P1	Single	normal concrete	200/250	225	1200	2 nos. of 8 mm bars	3 nos. of 10 mm bars	mm @ 100 mm c/c
Q1	Single	Microconcrete	200/250	225	1200	2 nos. of 10 mm bars	3 nos. of 12 mm bars	mm @ 100 mm c/c
R2	double	non-retrofitted control beam	100/150	125	1200	-	-	-
P2	double	normal concrete	200/250	225	1200	2 nos. of 8 mm bars	3 nos. of 10 mm bars	mm @ 100 mm c/c
Q2	double	microconcrete	200/250	225	1200	2 nos. of 10 mm bars	3 nos. of 12 mm bars	mm @ 100 mm c/c

3.3.5 Supplies

To make sure that the component materials complied with conventional standards for the jacketing processes used to reinforce the first prestressed concrete beams, a number of fundamental tests were meticulously carried out on them. For this, two different materials were used. Ordinary Portland cement of grade 43 was the cement used.

As shown in table 4, the produced conventional normal concrete M35 has a design mix ratio of 1:1.07:2.25 in accordance with IS code 10262 [28], which produces an amazing compressive strength of 42 N/mm² after curing cube samples for 28 days. Important cement material characteristics, such as its specific gravity (3.14), usual consistency (30.5%), and setting durations (91 minutes for the first setting, 225 minutes for the last setting), were meticulously recorded.

The fine aggregates also showed specific gravity (2.5), moisture content (0.16%), water absorption (1.2%), and fineness modulus (2.8) after going through a 4.75 mm screen. The coarse aggregates used had a maximum size of 20 mm and a minimum size of 12.5 mm. They were defined by their specific gravity of 2.5, water absorption of 0.5%, and fineness modulus of 7.3. The attention to structural integrity and safety is shown by these stringent tests and requirements that guarantee the calibre and dependability of the materials used in the reinforcing of prestressed concrete beams.

Microconcrete is a formulated grout composed primarily of cement, designed to compensate for shrinkage and provide high flowability, making it ideal for jacketing and repair applications. Its use in strengthening enhances the structural integrity and load-bearing capacity of prestressed concrete elements, particularly in areas where conventional concrete placement is challenging. The microconcrete product used for jacketing prestressed concrete beams is SikaRep Microconcrete, known for its excellent mechanical properties, durability, and ease of application. To support informed decision-making in material selection and implementation, Table 5 provides a comprehensive overview of the key physical and mechanical properties of microconcrete, including compressive strength, setting time, flow characteristics, and density.

The steel reinforcement used in the jacketing process with microconcrete includes Fe500 TMT bars of 8 mm, 10 mm, and 12 mm diameters, selected for their high strength and ductility. These reinforcement bars play a critical role in enhancing the load-carrying capacity and overall structural performance of the retrofitted prestressed concrete beams. Comprehensive test results, presented in Table 6, provide valuable insights into the effectiveness and compatibility of these bars when used with the selected jacketing materials. The data confirm their suitability in achieving the desired structural enhancements, ensuring both safety and long-term durability.

To achieve a structurally sound and durable retrofit, it is essential to establish a strong bond between the existing concrete surface and the newly applied jacketing layer. Proper surface preparation, combined with the use of high-quality bonding agents, is crucial in this regard. One effective bonding chemical commonly used in such applications is Dr. Fixit, which enhances adhesion between old and new concrete surfaces, thereby improving the monolithic behavior of the retrofitted section. The combination of suitable reinforcement, quality jacketing materials, and reliable bonding agents ensures the longevity and stability of the strengthened structural elements.

Table 3.5: Mix design proportion (kg/m³) of conventional concrete

Cement (kg)	Water in litres	Coarse aggregate (kg)	Fine aggregate (kg)	Super plasticizer (litres)	Compressive Strength (MPa)	Tensile Strength (MPa)
72	38	77	162.82	2.412	42	4.5
w/c ratio: (by weight) 0.45, slump 25-100 mm						

Table 3.6: Mix design proportion (kg/m³) of micro-concrete

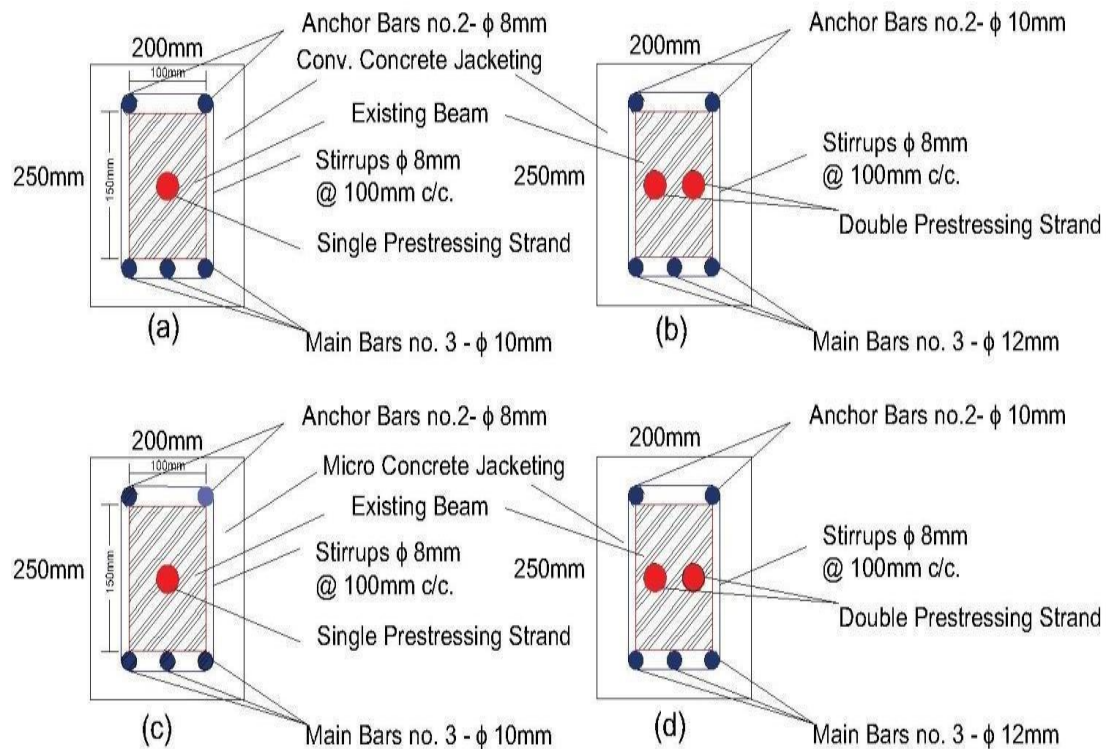
Microconcrete (kg)	Water in liters	Density kg/m ³	Comp. strength in 28 days N/mm ²	Split Tensile Test N/mm ²
180	27	2200	55	5.19

Table 3.7: Steel reinforcement test results

Bar size	Avg yield stress (MPa)	Avg ultimate stress (MPa)	Elongation (%)	Bending test (90)
8 mm	424.12	720.21	17.66	Pass
10 mm	444.32	690.34	17.24	Pass
12 mm	460.26	624.24	17.12	Pass

3.3.6. Design Details of Specimens

The cross-sectional dimensions for retrofitted prestressed concrete beams is shown in figure 4.2.



**Figure 3.9 Cross section of retrofitted prestressed concrete beams (a) beam P1
(b) beam P2 (c) beam Q1 (d) beam Q2**

3.3.7. Specimen Preparation

Beams R1 and R2, two of the six beams that received strengthening, were designated as control beams and were left undisturbed so that they could be used as comparison standards. On the other hand, beams P1, P2, Q1, and Q2 experienced jacketing processes with various reinforcement mixtures.

While beams Q1 and Q2 were strengthened using microconcrete mix jacketing, beams P1 and P2 were retrofitted with traditional regular concrete mix jacketing. Figure 4.4 provides a clear visual picture of the reinforcing process and details the full jacketing operation.

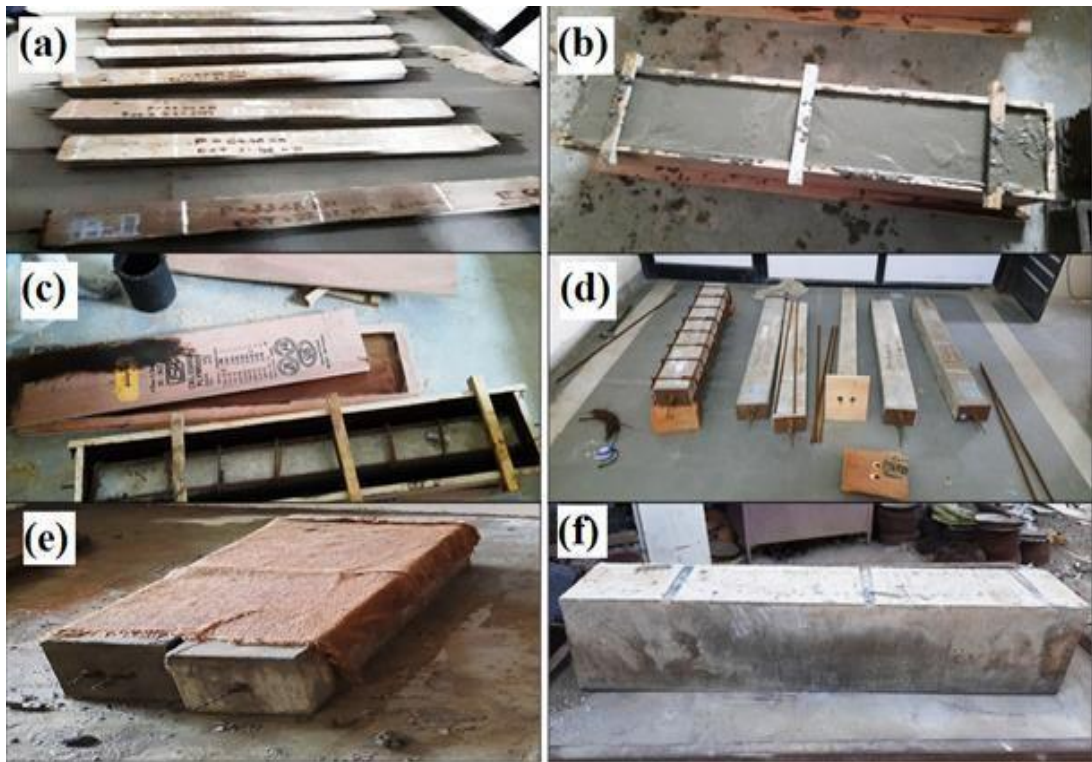


Figure 3.10 Jacketing Procedure (a) treatment of beam surface (b) reinforcement for beams (c) beams in wooden mould (d) concrete placing in moulds (e) curing of beams (f) specimen ready for testing

The jacketing procedure involves several systematic steps to enhance the structural performance of beams. First, the surface of the existing beam is thoroughly treated by roughening and cleaning to ensure proper bonding.

Next, additional reinforcement bars are placed around the beam, typically tied with existing stirrups for effective load transfer. The beam is then enclosed within a wooden mould to shape the jacket. Concrete is carefully placed into the mould, ensuring compaction to eliminate voids. After placement, proper curing is carried out to achieve the desired strength. Once cured, the specimen is ready for structural testing to evaluate performance improvements.

Following IS code 456 [29], steel mesh was appropriately fitted for each beam in a variety of combinations. The beams were then carefully placed into wooden moulds to provide correct alignment and support during the reinforcing procedure. Following the careful levelling of the freshly mixed conventional concrete and microconcrete mixtures into their corresponding wooden moulds, the beams' surfaces were made uniform. After pouring, the beams were left to cure for 28 days to maximise the hydration and strength development of the concrete. The reinforced beams underwent experimental testing once the curing phase was complete to assess their structural performance and durability under various loading scenarios.

Future construction practices and the integrity of reinforced concrete structures can be ensured by gaining important insights into the performance of the materials used and the effectiveness of the reinforcement techniques used through methodical experimentation and analysis.

3.3.8. Specimen Testing

Every beam was tested using a centre-point focused loading technique with simple supports. The IPS College of Engineering's strength of materials laboratory in Indore, Madhya Pradesh, India, was the site of the testing.

A loading frame with a 1000 kN maximum compressive load capability was installed in the lab. A hydraulic jack was used to carry out the loading process after each beam specimen was carefully placed on the loading frame. To provide exact control and measurement of the loading conditions, the applied load was then precisely measured and transmitted to the beams by a load cell.

The experimental setup shown in Figure 3.10 enabled a thorough assessment of the reinforced beams' structural performance and load-bearing capability, yielding significant insights for further study and optimisation of reinforcing methods.



Figure 3.11 Loading frame in the laboratory

The beam was positioned with great care across two supports, 100 mm from each end. The beam, which had an effective length of 1000 mm, was subjected to a 5 kN single-point load increase delivered at its centre. A dial gauge with a least count of 0.01mm was positioned exactly at the middle of the beam to measure the deflection there.

Deflection measurements were carefully recorded at different load increments throughout the loading operation. Important characteristics, including the load at the point at which fractures first appeared and at the point of final failure, were recorded as loading proceeded until failure.

Throughout the test, the formation of fractures and their patterns were continuously observed and recorded. Cracks were indicated with chalk to draw attention to the failure patterns and make it easier to observe and analyse the structural behaviour of the beam under increasing load scenarios.

3.3.9 Summary

The chapter provides a comprehensive methodology for retrofitting prestressed concrete beams, emphasizing experimental analysis, careful material selection, and precise application techniques to enhance both structural performance and long-term durability. The methodology is rooted in the goal of restoring or improving the load-bearing capacity of deteriorated beams while maintaining structural integrity and serviceability.

A key focus of the study is the concrete's ability to resist degradation throughout its intended service life without the need for frequent or costly maintenance. To achieve this, repair materials must possess essential characteristics such as low shrinkage, appropriate setting and hardening times, consistent performance under variable site conditions, strong adhesion to the existing substrate, thermal compatibility with the parent concrete, and low permeability to resist moisture and chemical ingress.

The study evaluates various repair and jacketing materials, including premixed cementitious mortars, polymer-modified mortars, epoxy resins, and a range of additives and admixtures specifically designed to improve mechanical properties, bonding strength, and workability. The use of self-compacting microconcrete is also highlighted for its ability to fill voids and conform to complex geometries without vibration.

CHAPTER 4

RESULT & DISCUSSION

4.1 Capacity to Carry Loads

As seen in figure 5.1 and table 7, the result data demonstrates the significant improvement in load carrying capacity obtained by jacketing prestressed concrete beams, especially with the use of microconcrete as the jacketing material. It also highlights the significant impact of jacketing materials on the structural performance of the beam.

4.1.1 Strengthened Prestressed Concrete Beams with a Single Strand:

In the absence of jacketing, the load-bearing capacity is around 20.0 kN, which provides a starting point for assessing the value of jacketing. Normal Concrete with Jacketing: Increases load capacity to 60.4 kN. Microconcrete: the material's higher performance as a jacketing material for single strand beams is shown by its improved load bearing capability, which increased to 90.2 kN.

4.1.2 Strengthened Prestressed Concrete Beams with a Double Strand:

Without Jacketing: The second prestressed strand raises the baseline load bearing capability to 25.8 kN. Normal Concrete with Jacketing: Significantly increased load capacity to 80.2 kN range. In a similar vein, microconcrete jacketing increases the load capacity of double strand beams to 120.6 kN, demonstrating how well it enhances structural robustness.

Table 4.1: Load carrying capacity and failure modes of Strengthened Single Strand Prestressed Concrete Beams

Beam	Cracking Load		Ultimate Capacity		Failure
	Load kN	Deflection mm	Load kN	Deflection mm	
P-1	30.1	3.5	60.4	4.2	Shear
Q-1	40.3	2.8	90.2	4.7	Flexure
R-1	08.6	2.0	20.0	2.5	Flexure

Table 4.2: Load carrying capacity and failure modes of Strengthened Double Strand Prestressed Concrete Beams

Beam	Cracking Load		Ultimate Capacity		Failure
	Load kN	Deflection mm	Load kN	Deflection mm	
P-2	45.2	3.7	80.2	4.4	Shear
Q-2	50.3	3.8	120.6	4.8	Shear
R-2	10.1	2.2	25.8	2.7	Flexure

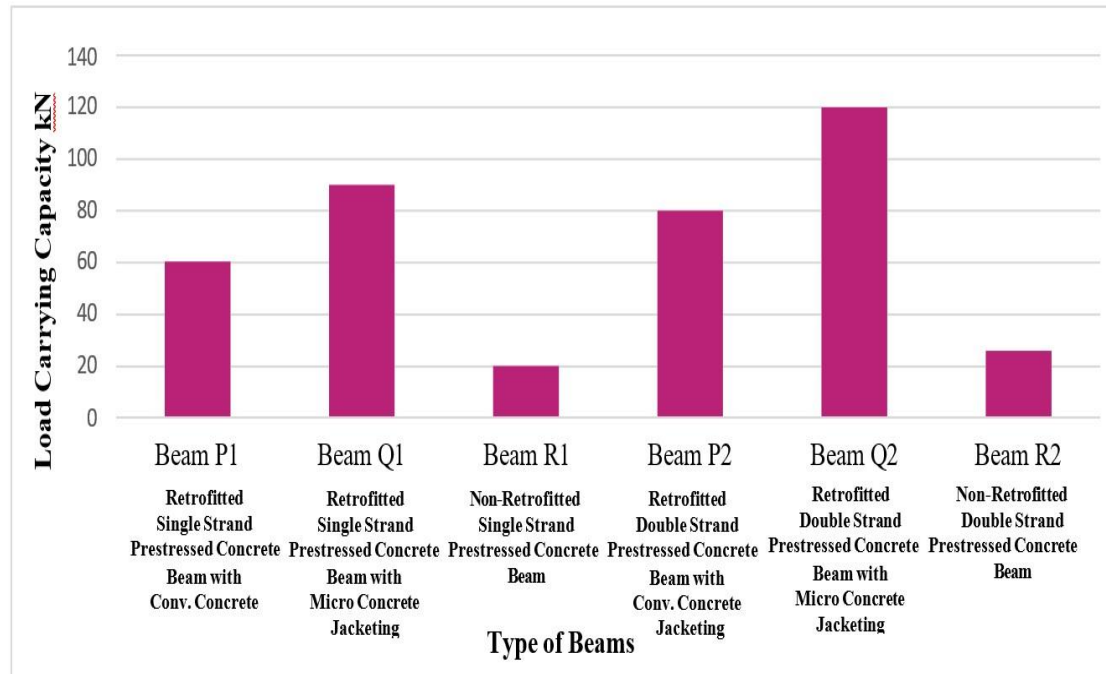


Figure 4.1 Load carrying capacity of strengthened prestressed concrete beams

These results indicate that retrofitting single and double strand prestressed concrete beams significantly increases their load bearing capability, with microconcrete jacketing exhibiting the greatest boost. The jacketing approach has the potential to enhance beam performance in other areas, such as durability and ductility, in addition to increasing load bearing capacity. The enhancement highlights how well jacketing methods work to strengthen and reinforce prestressed concrete buildings to bear larger loads and enhance overall structural performance, especially when microconcrete is used.

4.2. Change of location

Experiments on the deflection behaviour of prestressed concrete beams under varying loads provide important information on how well retrofitting methods using various jacketing materials work. The research illustrates how jacketing materials affect beam deformability by measuring deflections at mid-span using a dial gauge system at intervals of every 5 kN load till failure.

The findings reveal that the retrofitted beams, both types—jacketed with conventional normal concrete and with micro-concrete— show greater deformability when compared to the non-retrofitted control beams (figure 5.3). The micro-concrete-jacketed beams (Q-1 and Q-2) showed significantly better deformability than the conventional normal concrete-jacketed beams (P-1 and P-2). The ductility of the micro-concrete material, which permits more extensive plastic deformation under stresses, is responsible for this higher performance. The least deformable control beams were the non-retrofitted R-1 and R-2, demonstrating how well jacketing works to enhance prestressed concrete beam performance.

The reduced ductility of the control beams emphasises the intrinsic limits of prestressed concrete beams that have not been modified with regard to their ability to absorb energy and flex under load. These results indicate that retrofitting single and double strand prestressed concrete beams significantly increases their load bearing capability, with microconcrete jacketing exhibiting the greatest boost. The jacketing approach has the potential to enhance beam performance in other areas, such as durability and ductility, in addition to increasing load bearing capacity. The enhancement highlights how well jacketing methods work to strengthen and reinforce prestressed concrete buildings to bear larger loads and enhance overall structural performance, especially when microconcrete is used. Experiments on the deflection behaviour of prestressed concrete beams under varying loads provide important information on how well retrofitting methods using various jacketing materials work. The research illustrates how jacketing materials affect beam deformability by measuring deflections at mid-span using a dial gauge system at intervals of every 5 kN load till failure. The findings reveal that the retrofitted beams, both types—jacketed with conventional normal concrete and with micro-concrete— show greater deformability when compared to the non-retrofitted control beams (figure 5.3). The micro-concrete-jacketed beams (Q-1 and Q-2) showed significantly better deformability than the conventional normal concrete-jacketed beams (P-1 and P-2). The ductility of the micro-concrete material, which permits more extensive plastic deformation under stresses, is responsible for this higher performance. The least deformable control beams were the non-retrofitted R-1 and R-2, demonstrating how well jacketing works to enhance prestressed concrete beam performance. The reduced ductility of the control beams emphasises the intrinsic limits of prestressed concrete beams that have not been modified regarding their ability to absorb energy and flex under load.

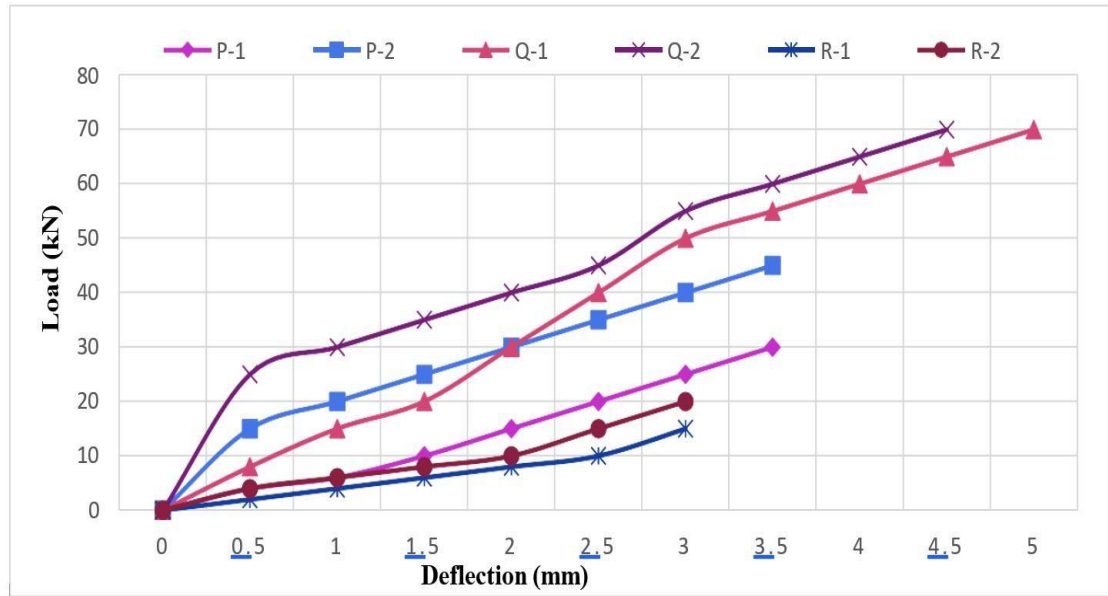


Figure 4.2 Comparison of Load Deflection Curves for Prestressed Concrete Beams with and without Jacketing

The behaviour that has been observed lends credence to the idea that retrofitting with ductile materials, such as micro-cement concrete, not only increases the load-bearing capacity but also greatly improves the overall safety and performance of the structure by making the beams more pliable and able to deform without failing right away. The research concludes that adding jacketing materials, particularly micro-concrete to prestressed concrete beams significantly increases their ductility and deformability. For structural applications where load resistance and plastic deformation resistance are critical, this enhancement is essential. The improved deformability of retrofitted beams, especially those jacketed with micro-concrete, marks a major advancement in the design and maintenance of prestressed concrete structures and provides a way ahead for the construction of infrastructure and buildings that are safer, more robust, and more resilient. This study demonstrates that jacketing with micro-concrete not only strengthens weakened or under-designed beams but also extends their service life by increasing resistance to cracking, corrosion, and fatigue.

4.3 Crack Pattern and Failure Mode

When Beam P1 was retrofitted using standard conventional concrete as the jacketing material, the first visible cracks were observed at an applied load of 40 kN. The mode of failure was attributed to shear, and the collapse occurred at a location approximately 42 cm from the right support toward the centre of the beam span. The observed crack pattern and failure zone are illustrated in Figure 4.3(a).

Although failure eventually occurred, the standard concrete jacketing contributed to a slight enhancement in load-bearing capacity compared to the non-retrofitted control beam. The retrofitting delayed the initiation of cracking to a marginally higher load level. At the point of failure, the maximum crack width recorded in Beam P1 was 12 mm, indicating a significant level of distress in the structure.

In contrast, Beam Q1 retrofitted with self-compacting microconcrete demonstrated a higher initial cracking load of 50 kN, signalling an improved resistance to early-stage cracking. This increase in cracking threshold reflects the superior bonding and flowability characteristics of microconcrete, which allow for better stress distribution and adherence between the jacket and the original concrete surface. Compared to both the control and conventionally jacketed beams, Beam Q1 exhibited enhanced structural performance, making microconcrete a more effective material for jacketing applications.



Figure 4.3 shows the crack pattern for (a) Beam P-1 (b) Beam Q-1 (c) Beam R-1

As shown in figure 4.3(b), the beam failed in flexure, with the failure point located 48 cm from the left support towards the centre. The maximum fracture width for this beam was 15 mm, which is a little broader than usual. This suggests that while microconcrete increases the load capacity of the beam and changes the failure mode to one that may be less abrupt, it may also result in somewhat wider cracks at the site of failure. At a much lower stress of 10 kN, the control beam R1, which was not jacketed, began to exhibit early fractures and eventually failed in flexure. As shown in figure 4.3(c), the central section of the beam was where the fractures were most often seen. The control beam's early cracking commencement clearly shows how efficient jacketing is in postponing crack initiation and enhancing overall structural performance.

When Beam P2 was retrofitted with regular, ordinary concrete, shear failure was seen 38 centimetres from the left support towards the centre. The first cracking occurred at a load of 50 kN. A diagram of the crack pattern may be seen in figure 4.4(a). The highest fracture width in this beam was 12 mm at the time of failure, which suggests that the typical standard concrete jacketing gave it some durability even if shear pressures finally caused it to collapse. When compared to traditional standard concrete jacketing, Beam Q2, which was jacketed with microconcrete, demonstrated early breaking at a greater stress of 70 kN, suggesting an enhanced resistance to initial cracking. But it too failed in shear, with the failure point being 20 cm in the middle, away from the right support. Figure 4.4(b) depicts this beam's fracture pattern. The maximum fracture width for this beam was somewhat bigger at 15 mm, despite the higher threshold for first cracking. This suggests that while microconcrete may provide superior initial crack resistance, it may also result in broader fissures upon failure.

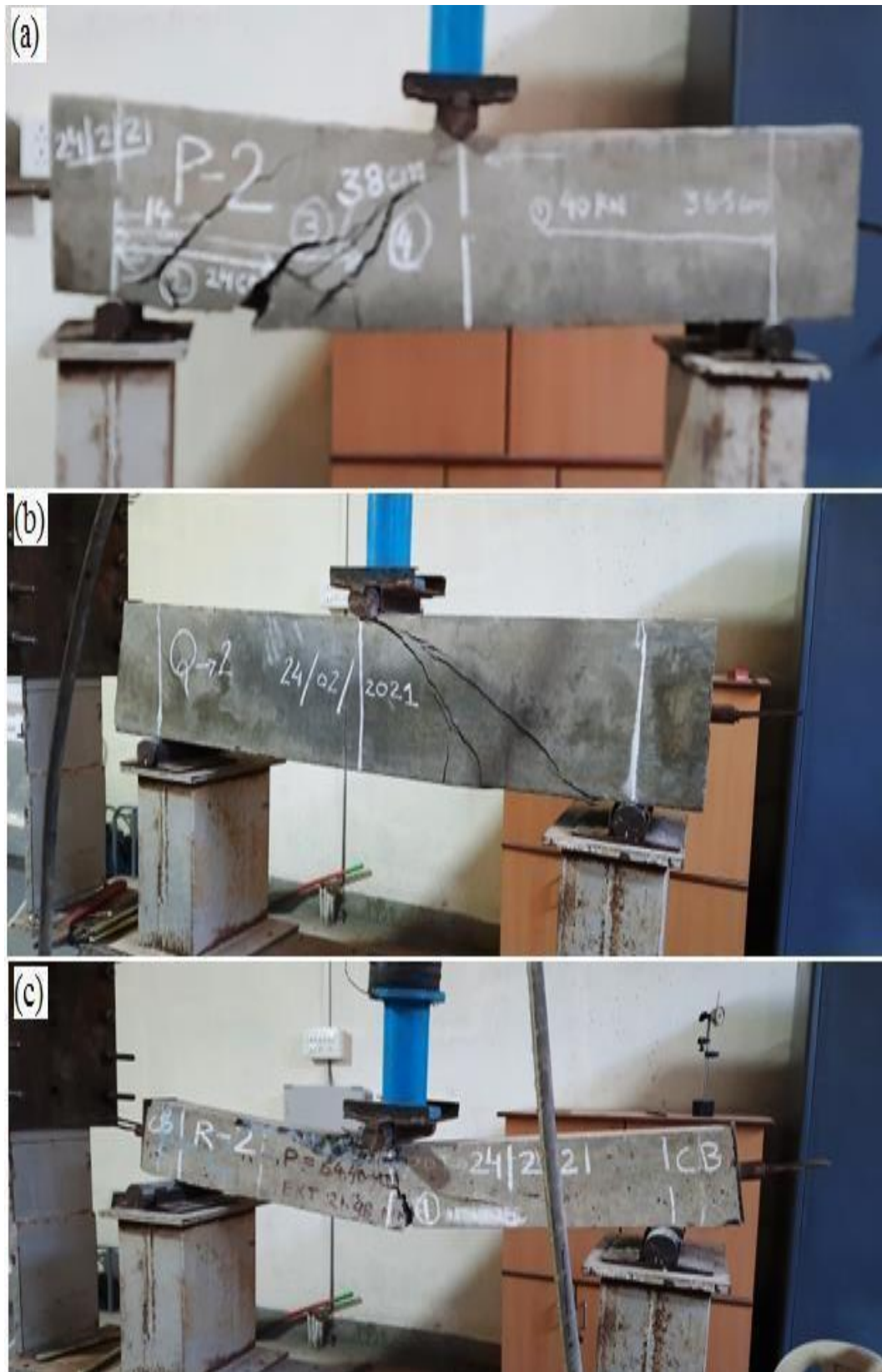


Figure 4.3 shows the crack pattern for (a) Beam P-1 (b) Beam Q-1 (c) Beam R-1

When compared to its retrofitted counterparts, the control beam R2 without any jacketing showed far less resistance to first cracking, with cracks appearing at a much lower stress of 15 kN. As seen in figure 4.4(c), the beam failed under shear, with fractures centred in the central region. Because of the reduced initial crack load, retrofitting has a significant positive impact on load-bearing capacity and delays the commencement of cracking.

Retrofitting plays a crucial role in enhancing shear resistance and postponing the onset of cracks in prestressed concrete beams. While both traditional normal concrete and microconcrete jacketing techniques improve the performance of prestressed concrete beams, their characteristics differ with respect to failure load and crack width.

Although microconcrete jacketing may result in bigger fissures at ultimate load, it enables a greater load capacity prior to first cracking, indicating a relationship between the breadth of the crack and the resistance to early cracking. The results have great significance for engineering purposes, as the selection of jacketing material may be maximised by taking certain structural constraints and performance standards into account.

4.4 Remarks

The use of jacketing materials greatly increases the prestressed concrete beams' structural capability. This research shows that both single and double strand prestressed concrete beams perform better when it comes to boosting their load bearing capability when microconcrete jacketing is used. The following conclusions were drawn considering the outcomes of the experimental investigations:

Compared to the similar beams without strengthening, a significant improvement in load bearing capacity and cracking load was seen in the retrofitted prestressed concrete beams. This improvement demonstrates how well retrofitting methods work to improve the resilience and performance of structures.

The load-bearing capability of prestressed concrete beams retrofitted with regular concrete jacketing is greatly increased; an increase of 200% to 220% is seen when compared to equivalent beams without strengthening

Compared to equivalent beams without strengthening, retrofitting prestressed concrete beams with microconcrete jacketing results in a striking 300% to 380% increase in load-carrying capability.

The reinforced beams showed less cracks than the similar beams without strengthening, and the rate of fracture growth was also decreased. Its ductility is significantly increased by 66% when microconcrete is used as a jacketing material, demonstrating a notable improvement in its capacity to flex under stress without failing.

To sum up, the use of microconcrete jacketing in prestressed concrete beams is a very effective retrofitting method that provides observable gains in strength, durability, ductility, and surface quality. Microconcrete's self-compacting feature makes application simple and guarantees a smooth finish, and its superior bonding capabilities ensure that it blends in with the existing structure, reducing the chance of bond failure. The advantages that microconcrete jacketing offers make it an excellent technique for improving the lifespan and performance of prestressed concrete structures. It is possible to do more research to examine the efficacy of different strengthening techniques.

CHAPTER 5

FINDINGS AND CONCLUSIONS

5.1 Findings

The application of jacketing materials significantly enhances the structural capacity of prestressed concrete beams. This study demonstrates that microconcrete jacketing offers superior performance in increasing the load carrying capacity of both single and double-strand prestressed concrete beams. The conclusion made on basis of the results obtained from experimental investigations are as follows:

1. In retrofitted prestressed concrete beams, a notable increase in load-carrying capacity and cracking load was observed compared to the corresponding beams without strengthening. This enhancement underscores the effectiveness of retrofitting techniques in enhancing structural performance and resilience.
2. Retrofitting prestressed concrete beams with normal concrete jacketing significantly boosts load carrying capacity, as an increase of 200% to 220% is observed as compared to corresponding beams without strengthening.
3. Retrofitting prestressed concrete beams with micro-concrete jacketing yields a remarkable 300% to 380% increase in load-carrying capacity as compared to corresponding beams without strengthening.
4. The rate of crack development was also reduced, and the strengthened beams exhibited fewer cracks compared to the corresponding beams without strengthening. The use of micro-

concrete as a jacketing material contributes to a significant 66% enhancement in the ductility, indicating a substantial improvement in its ability to deform under stress without failing

5. In conclusion, the application of micro-concrete jacketing to prestressed concrete beams stands out as a highly efficient retrofitting solution, offering notable improvements in ductility, strength, durability, and surface finish. The self-compacting nature of micro-concrete facilitates easy application and ensures a high-quality finish, while its excellent bonding properties guarantee compatibility with the existing structure, minimising the risk of bond failure. This combination of benefits underscores micro-concrete jacketing as a superior method for enhancing the performance and longevity of prestressed concrete structures.

5.2 Conclusions

Improved Load-Bearing Capacity: Retrofitting prestressed concrete beams with jacketing significantly enhances their load-bearing capacity. The added reinforcement provides additional strength, allowing the beams to support greater loads than their original design specifications. This improvement is crucial for extending the service life of existing structures and adapting them to increased load demands.

Enhanced Structural Integrity: The jacketing process improves the overall structural integrity of prestressed concrete beams. By encasing the beams in a new layer of high-strength materials, the likelihood of cracking and other forms of deterioration is reduced. This added protection helps maintain the structural integrity of the beams under various stress conditions.

Increased Durability: Jacketing enhances the durability of prestressed concrete beams by protecting them from environmental factors such as moisture, temperature fluctuations, and chemical exposure. The new layer acts as a barrier, preventing these factors from penetrating the concrete and causing long-term damage.

Improved Ductility: Retrofitting with jacketing improves the ductility of prestressed concrete beams, making them more resistant to seismic and dynamic loads. The jacketing allows the beams to deform more easily under stress, absorbing energy and reducing the likelihood of sudden failure.

Cost-Effective Rehabilitation: Jacketing is a cost-effective method for rehabilitating prestressed concrete beams compared to complete replacement. The process is less disruptive and can be completed more quickly, minimising downtime and reducing overall project costs.

Versatility in Application: Jacketing can be applied to a wide range of beam sizes and shapes, making it a versatile solution for various structural rehabilitation projects. Whether dealing with small-scale beams in residential buildings or large-scale beams in bridges and industrial structures, jacketing can be tailored to meet specific requirements.

Positive Long-Term Performance: Retrofitted beams have been shown to perform well under continued use, maintaining their enhanced properties over time and providing a reliable solution for extending the lifespan of existing structures.

Sustainability Benefits: By extending the life of existing structures, jacketing contributes to sustainability efforts by reducing the need

for new construction materials and minimising construction waste. This aligns with modern engineering practices focused on sustainability and environmental conservation.

In summary, retrofitting prestressed concrete beams with jacketing is an effective method to enhance their load-bearing capacity, structural integrity, durability, and ductility. It offers a cost-effective, versatile, and sustainable solution for extending the lifespan and performance of existing structures, making it a valuable technique in the field of structural engineering.

Further studies can be undertaken to explore the effectiveness of various other strengthening methods.

REFERENCES

- [1] Abeles, P.W. (1966). Principles of prestressed concrete. London: Wiley.
- [2] Al-Azzawi, S., & Obeid, S. (2019). Structural performance of reinforced concrete beams. *Journal of Civil Engineering Research and Practice*, 8(2), 145-158.
- [3] Altoubat, S. A., et al. (2018). "Shear Behavior of Prestressed Concrete Beams." *Journal of Structural Engineering*, 144(9).
- [4] Anagnostou, G., et al. (2020). "Shear Strength of Prestressed Concrete Beams." *Engineering Structures*, 205.
- [5] Aschheim, M. A., et al. (2018). "Long-term Behavior of Prestressed Concrete Beams: Effects of Creep and Shrinkage." *ACI Structural Journal*, 115(6).
- [6] Aref, A. J., & Al-Hammoud, R. (2018). "Strengthening of Concrete Structures Using FRPs." *Journal of Composites for Construction*, 22(3).
- [7] Black, C., et al. (2018). "Buckling-Restrained Braces for Seismic Retrofitting." *Earthquake Engineering & Structural Dynamics*, 47(5).
- [8] Barnett, S. J., et al. (2018). "Fiber-Reinforced Polymers in Prestressed Concrete Beams." *Composites Part B: Engineering*, 152.
- [9] Buyukozturk, O., et al. (2019). "Interaction of Shear Reinforcement and Prestress Forces." *Engineering Fracture Mechanics*, 212.

- [10] Bazant, Z. P., & Cedolin, L. (2010). *Stability of Structures: Elastic, Inelastic, Fracture and Damage Theories*. World Scientific.
- [11] Bendsoe, M. P., & Sigmund, O. (2003). *Topology Optimization: Theory, Methods and Applications*. Springer.
- [12] Chopra, A. K. (2007). *Dynamics of Structures: Theory and Applications to Earthquake Engineering*. Prentice Hall.
- [13] Cao, J., et al. (2018). *Application of Pre-Stressed CFRP Laminates. Composite Structures*.
- [14] Chen, X., et al. (2021). Load distribution in high-rise building structures. **Structural Engineering Review*, 15(3), 210-225.
- [15] Chen, J. F., & Teng, J. G. (2019). *Shear Strengthening Using FRP and Steel Combinations. Composite Structures*.
- [16] Collins, M.P., & Mitchell, D. (2003). *Prestressed concrete structures*. Toronto: University of Toronto Press.
- [17] Constantinou, M. C., et al. (2018). "Seismic Isolation Systems for Building Structures." *Journal of Structural Engineering*, 144(6).
- [18] DesRoches, R., & McCormick, J. (2018). *Seismic Retrofitting Using Shape Memory Alloys. Journal of Structural Engineering*.
- [19] De Lorenzis, L., & Nanni, A. (2019). *Near-Surface Mounted FRP Reinforcement: State-of-the-Art Review. Journal of Composites for Construction*.
- [20] De Lorenzis, L., & Nanni, A. (2019). "Near-Surface Mounted FRP Reinforcement: State-of-the-Art Review." *Journal of Composites for Construction*, 23(1).

- [21] DesRoches, R., & McCormick, J. (2018). "Seismic Retrofitting Using Shape Memory Alloys." *Journal of Structural Engineering*, 144(3).
- [22] DesRoches, R., & McCormick, J. (2018). "Seismic Retrofitting Using Shape Memory Alloys." *Journal of Structural Engineering*, 144(3).
- [23] De Lorenzis, L., & Nanni, A. (2019). "Near-Surface Mounted FRP Reinforcement: State-of-the-Art Review." *Journal of Composites for Construction*, 23(1).
- [24] DesRoches, R., & McCormick, J. (2017). "Application of Shape Memory Alloys in Seismic Retrofitting." *Journal of Intelligent Material Systems and Structures*, 28(3).
- [25] El-Maaddawy, T., et al. (2020). "Performance of NSM FRP Systems in Strengthening Concrete Structures." *Construction and Building Materials*, 243.
- [26] Filippou, F. C., et al. (2019). "Finite Element Modeling of Retrofitted Prestressed Concrete Beams." *Engineering Structures*, 189.
- [27] Fang, Y., et al. (2022). High-strength steel in beam construction: Benefits and challenges. *Materials in Civil Engineering*, 34(6), 450-465.
- [28] Fardis, M. N. (2018). "Seismic Design, Assessment and Retrofitting of Concrete Buildings." Springer.

- [29] Filippou, F. C., et al. (2019). "Advanced Finite Element Modeling of Prestressed Concrete Beams." *Computers & Structures*, 213.
- [30] Filippou, F. C., et al. (2019). "Numerical Modelling of Retrofitted Structures." *Engineering Structures*, 167.
- [31] Graybeal, B. A. (2019). Ultra-High-Performance Concrete for Infrastructure Retrofitting. *ACI Materials Journal*.
- [32] Graybeal, B. A. (2019). "Ultra-High-Performance Concrete for Infrastructure Retrofitting." *ACI Materials Journal*, 116(5).
- [33] Grelle, S. V., & Sneed, L. H. (2018). Performance of Retrofitted Beams in Fire Conditions. *Fire Safety Journal*.
- [34] Gou, X., et al. (2019). Smart beams for real-time structural health monitoring. *Sensors and Actuators in Civil Engineering*, 11(4), 335-350.
- [35] Graybeal, B. A., & Hartmann, J. (2019). "Ultra-High-Performance Concrete in Prestressed Beams." *PCI Journal*, 64(2).
- [36] Hou, H., et al. (2019). "Behavior of Beams Prestressed with Bonded and Unbonded Tendons." *Construction and Building Materials*, 227.
- [37] Hewson, N.R. (1997). *Prestressed concrete bridges: Design and construction*. London: ICE Publishing.
- [38] Johnson, R. P., & Anderson, D. (2013). *Designers' Guide to EN 1994-1-1: Eurocode 4: Design of Composite Steel and Concrete Structures*. Thomas Telford.

- [39] Kumar, A., et al. (2022). Earthquake-resistant beam design for reinforced concrete structures. *Seismic Safety Journal*, 27(1), 110-125.
- [40] Kim, H. J., et al. (2019). Retrofitting with High-Strength Steel Strands. *Construction and Building Materials*.
- [41] Kang, S. H., et al. (2020). Use of Hybrid FRP Systems for Retrofitting. *Composites Part B: Engineering*.
- [42] Keller, T. (2003). Use of Fiber Reinforced Polymers in Bridge Construction. In *Advanced Polymer Composites for Structural Applications in Construction*. Springer.
- [43] Lee, D., et al. (2020). Advances in beam theory and applications. *Journal of Advanced Structural Engineering*, 22(5), 380-395.
- [44] Li, H., et al. (2020). Wind-resistant design of beams in tall buildings. *Journal of Wind Engineering*, 16(3), 275-290.
- [45] Lin, T.Y. (1955). *Design of prestressed concrete structures*. New York: Wiley.
- [46] Lam, D., & El-Lobody, E. (2005). Behavior of Composite Steel-Concrete Beams at Large Deflections. *Journal of Constructional Steel Research*, 61(11), 1625-1640.
- [47] Leonhardt, F. (1964). *Prestressed Concrete Design and Construction*. Wilhelm Ernst & Sohn.
- [48] Mander, J. B., et al. (2018). Seismic Retrofit of Prestressed Concrete Bridges Using Steel Jackets. *Journal of Bridge Engineering*.

- [49] Mazzotti, C., & Savoia, M. (2019). Performance Evaluation of Prestressed Beams with CFRP. Composite Structures.
- [50] MacGregor, J. G., & Wight, J. K. (2012). Reinforced Concrete: Mechanics and Design. Prentice Hall.
- [51] McCormac, J. C., & Brown, R. H. (2015). Design of Reinforced Concrete. Wiley.
- [52] Mast, R.F. (2018). Long-term performance of prestressed concrete beams. Journal of Structural Engineering, 144(6), 04018069.
- [53] Mehta, P. K., & Monteiro, P. J. M. (2017). "Sustainable Construction: Use of Recycled Materials in Prestressed Concrete." Cement and Concrete Composites, 79.
- [54] Mazzoni, S., et al. (2018). "Finite Element Analysis of Retrofitted Structures." Computers & Structures, 213.
- [55] Mander, J. B., et al. (2018). "Seismic Retrofit of Prestressed Concrete Bridges Using Steel Jackets." Journal of Bridge Engineering, 23(4).
- [56] Mander, J. B., et al. (2018). "Seismic Retrofit of Prestressed Concrete Bridges Using Steel Jackets." Journal of Bridge Engineering, 23(4).
- [57] Naeim, F., & Kelly, J. M. (2020). "Base Isolation Systems for Seismic Retrofitting." Earthquake Engineering & Structural Dynamics, 49(6).
- [58] Naeim, F., & Kelly, J. M. (2020). *Base Isolation Systems for Seismic Retrofitting*. Earthquake Engineering & Structural Dynamics.

- [59] Naeim, F., & Kelly, J. M. (2020). "Base Isolation Systems for Seismic Retrofitting." *Earthquake Engineering & Structural Dynamics*, 49(6).
- [60] Naeim, F., & Kelly, J. M. (2020). "Design of Seismic Isolated Structures." John Wiley & Sons.
- [61] Nawy, E. G. (2009). *Prestressed Concrete: A Fundamental Approach*. Prentice Hall.
- [62] Nilson, A. H., Darwin, D., & Dolan, C. W. (2010). *Design of Concrete Structures*. McGraw-Hill.
- [63] Naaman, A.E. (2012). *Prestressed concrete analysis and design: Fundamentals* (3rd ed.). Ann Arbor: Techno Press 3000.
- [64] Ozdemir, G., et al. (2020). Strengthening of Beams Using Textile Reinforced Mortar. *Journal of Composites for Construction*.
- [65] Pan, J., & Leung, C. K. Y. (2018). *Retrofitting with Basalt Fiber Composites*. Construction and Building Materials.
- [66] Park, S., et al. (2021). Sensor-integrated beams for smart infrastructure. *Journal of Smart Structures and Systems*, 29(7), 501-517.
- [67] Patel, R., et al. (2020). Sustainable beam design using recycled materials. *Journal of Green Construction*, 12(4), 360-375.
- [68] Pacheco-Torgal, F., et al. (2018). "Environmental Impact of Prestressed Concrete: A Review." *Journal of Cleaner Production*, 198.

- [69] Palkovic, S. D., et al. (2017). "Nonlinear Flexural Behavior of Prestressed Beams." *Structural Concrete*, 18(1).
- [70] Pacheco-Torgal, F., et al. (2018). Sustainable Retrofitting of Concrete Structures Using Recycled Materials. *Journal of Cleaner Production*.
- [71] Pellegrino, C., & Modena, C. (2018). FRP Strengthening of Concrete Structures: A Review of Design Guidelines. *Construction and Building Materials*.
- [72] Pacheco-Torgal, F., & Jalali, S. (2018). "Sustainable Construction Materials for Retrofitting." *Journal of Cleaner Production*, 198.
- [73] Park, J., et al. (2020). "Monitoring of Retrofitted Structures Using Laser Scanning." *Automation in Construction*, 113.
- [74] Paulay, T., & Priestley, M. J. N. (2019). "Seismic Design of Reinforced Concrete and Masonry Buildings." John Wiley & Sons.
- [75] Pacheco-Torgal, F., et al. (2018). "Sustainable Retrofitting of Concrete Structures Using Recycled Materials." *Journal of Cleaner Production*, 197.
- [76] Pellegrino, C., & Modena, C. (2018). "FRP Strengthening of Concrete Structures: A Review of Design Guidelines." *Construction and Building Materials*, 214.
- [77] Pacheco-Torgal, F., et al. (2018). "Sustainable Retrofitting of Concrete Structures Using Recycled Materials." *Journal of Cleaner Production*, 197.
- [78] Pellegrino, C., & Modena, C. (2018). "FRP Strengthening of Concrete Structures:

A Review of Design Guidelines." Construction and Building Materials, 214.

- [79] Saiidi, M. S., et al. (2020). "Innovative Seismic Retrofitting of Bridges Using Shape Memory Alloys." Journal of Bridge Engineering, 25(2).
- [80] Spacone, E., et al. (2018). "Advanced Numerical Modeling of Retrofitted Concrete Beams." Computers & Structures, 195.
- [81] Sutton, M. A., et al. (2019). "Application of Digital Image Correlation in Retrofitting Assessment." Journal of Structural Engineering, 145(6).
- [82] Saiidi, M. S., et al. (2020). "Innovative Seismic Retrofitting of Bridges Using Shape Memory Alloys." Journal of Bridge Engineering, 25(2).
- [83] Spacone, E., et al. (2018). "Advanced Numerical Modeling of Retrofitted Concrete Beams." Computers & Structures, 195.
- [84] Sutton, M. A., et al. (2019). "Application of Digital Image Correlation in Retrofitting Assessment." Journal of Structural Engineering, 145(6).
- [85] Sabelli, R., et al. (2019). "Seismic Retrofitting Using Buckling-Restrained Braces." Earthquake Spectra, 35(2).
- [86] Saiidi, M. S., et al. (2019). "Shape Memory Alloys for Seismic Retrofitting of Bridges." Journal of Bridge Engineering, 24(3).
- [87] Sutton, M. A., et al. (2019). "Digital Image Correlation for Structural Monitoring." Experimental Mechanics, 59(6).

- [88] Sutton, M. A., et al. (2019). Application of Digital Image Correlation in Retrofitting Assessment. *Journal of Structural Engineering*.
- [89] Spacone, E., et al. (2018). "Finite Element Analysis of Prestressed Concrete Beams." *Engineering Structures*, 167.
- [90] Spacone, E., et al. (2018). Advanced Numerical Modeling of Retrofitted Concrete Beams. *Computers & Structures*.
- [91] Saiidi, M. S., et al. (2020). Innovative Seismic Retrofitting of Bridges Using Shape Memory Alloys. *Journal of Bridge Engineering*.
- [92] Sutton, M. A., et al. (2019). "Digital Image Correlation in Experimental Mechanics." *Experimental Mechanics*, 59(6).
- [93] Smith, S. T., & Teng, J. G. (2020). Experimental Study on CFRP Prestressing Techniques. *Journal of Composites for Construction*.
- [94] Sikorsky, C. S., Brownjohn, J. M. W., & Taylor, C. A. (2019). Smart Beams: Structural Health Monitoring of Bridges. *Proceedings of the Institution of Civil Engineers - Bridge Engineering*, 172(2), 107-119.
- [95] Shah, S.P., & Ouyang, C. (2016). Advances in materials and techniques for prestressed concrete. *Materials and Structures*, 49(8), 3137-3151.
- [96] Singh, R., et al. (2021). Composite materials in beam construction: A review. *Composite Structures Journal*, 25(6), 445-460.
- [97] Tam, V. W. Y., et al. (2019). "Recycled Materials in Concrete for Sustainable Retrofitting." *Resources, Conservation and Recycling*, 142.

- [98] Tang, X., & Saadatmanesh, H. (2019). "Use of FRPs in Retrofitting of Concrete Structures." *Journal of Composites for Construction*, 23(1).
- [99] Tremblay, R., et al. (2018). "Steel Braces in Seismic Retrofitting." *Journal of Constructional Steel Research*, 148.
- [100] Tam, V. W. Y., et al. (2019). "Use of Recycled Materials in Concrete for Sustainable Retrofitting." *Resources, Conservation and Recycling*, 150.
- [101] Triantafillou, T. C., et al. (2019). "Effectiveness of FRP Composites in Retrofitting Prestressed Concrete Beams." *Composites Part B: Engineering*, 160.
- [102] Tam, V. W. Y., et al. (2019). "Use of Recycled Materials in Concrete for Sustainable Retrofitting." *Resources, Conservation and Recycling*, 150.
- [103] Timoshenko, S. P., & Gere, J. M. (1961). *Theory of Elastic Stability*. McGraw-Hill.
- [104] Tan, K., et al. (2021). Wind load considerations in beam design. *Journal of Structural Dynamics*, 20(2), 180-195.
- [105] Teng, J. G., et al. (2020). Hybrid Retrofitting Techniques Combining FRP and Steel. *Journal of Structural Engineering*.
- [106] Wille, K., & Naaman, A. E. (2020). "Ultra-High-Performance Concrete for Structural Retrofitting." *PCI Journal*, 65(3).

- [107] Wang, Y., et al. (2021). Green construction practices in beam design. *Sustainable Engineering Journal*, 14(3), 290-305.
- [108] Wille, K., et al. (2018). "Retrofitting Concrete Structures with UHPC." *Cement and Concrete Composites*, 92.
- [109] Wang, C. L., Salmon, C. G., & Pincheira, J. A. (2007). *Reinforced Concrete Design*. Wiley.
- [110] Wille, K., & Naaman, A. E. (2020). "Ultra-High-Performance Concrete for Structural Retrofitting." *PCI Journal*, 65(3).
- [111] Yoon, S., et al. (2020). "Acoustic Emission Monitoring of Retrofitted Concrete Structures." *Materials and Structures*, 53(1).
- [112] Zhang, L., et al. (2019). Performance of Retrofitted Beams under Dynamic Loading. *Journal of Structural Engineering*.
- [113] Zhang, X., & Xu, J. (2020). Pre-stressed concrete beams: Design and performance. *Concrete Research and Applications*, 19(4), 325-340.

APPENDIX

List of Research Papers and Conference Certificates

Analysis of Losses in Post-Tensioned Prestressed Concrete Beams

Ankur Verma¹, Dr A. Mahesh Babu²

¹ Research Scholar, Department of Civil Engineering, P.K. University, Thanara, Shivpuri, India

² Professor, Department of Civil Engineering, P.K. University, Thanara, Shivpuri, India

ABSTRACT

Prestressing is the process of introducing internal stresses in the member to counteract the tensile stresses resulting from external loads during the service period. It is done to increase the members' strength and durability and control the members' cracking and deflection. As prestress introduced into concrete does not remain same due to the losses of prestress occurs immediately and during the lifetime of the member. The prestress losses result into reduction in strength and serviceability of prestressed concrete members. These prestress losses are divided into 2 categories, immediate losses and time-dependent losses. The loss of prestress due to friction, anchorage slip and elastic shortening comes under immediate losses whereas the loss of prestress due to creep, shrinkage of concrete and relaxation of steel comes under time-dependent losses. The purpose of this paper is to study and evaluate prestress losses in post-tensioned prestressed concrete beams using IS code 1343:2012. Total 6 beams are used for comparative analysis of prestress losses in prestressed concrete beams. The beams having rectangular cross-section of 100 mm wide and 150 mm deep with span of 1200 mm. Out of 6 beams, 3 beams are provided with single strand comprising of 3 wires of diameter 3 mm and other 3 beams are provided with double strands comprising of 3 wires each with diameter of 3 mm. The profile of strand is parabolic in nature with eccentricity of 50 mm. The conclusion based on the measurement findings shows that percentage loss of initial prestressing force is in between 20 % to 26 % prestressed concrete beams. Moreover, the efficiency of single reinforced prestressed concrete beam is more than double reinforced prestressed concrete beams.

Keywords: Prestressed Concrete, Creep, Shrinkage, Losses of Prestress

corresponding author (e-mail: ankurverma2019@gmail.com)

1. INTRODUCTION

Prestressed concrete is a particular form of reinforced concrete. Prestressing involves the application of an initial compressive load to the structure to reduce or eliminate the internal tensile force and, thereby, control or eliminate cracking. It has long been recognized that the prestress introduced into concrete, does not remain constant but decreases gradually with the progress of time. In a pretensioned concrete, the loss of prestress is due to elastic shortening, friction, anchorage slip, creep, shrinkage and relaxation of steel. The losses are classified into immediate losses and time-dependent losses. Loss of prestress due to friction comes under immediate loss in prestress concrete.

It is due to the friction between tendons and material surrounding the tendon. Loss of prestress depends upon the cable profile of tendon and duct. In case of straight tendon, the effect of friction is based on length of tendon whereas in case of curved tendon, the loss of friction depends upon the curvature of duct

and also the frictional coefficient between the duct and tendon. Loss of prestress due to friction occurs only in post tensioned beams. Loss of prestress due to anchorage slip is an immediate loss in prestress concrete. The slip occurs during the jacking process of transferring prestress to concrete. The anchorage slip depends upon the type of wedges and initial stress in tendon. The loss of prestress due to anchorage slip happens in post tensioned beams. Loss of prestress due to creep in concrete is a time-dependent loss in prestress concrete. It is due to deformation of concrete due to sustained compressive stresses. The creep in concrete member depends upon the loading and its time interval on the member. Loss of prestress due to shrinkage in concrete is a time-dependent loss in prestress concrete. It is due to reduction in volume of concrete with respect to time. Shrinkage of concrete depends only on the interval of time and the moisture conditions, but is independent of the stresses in the member due to loads. Loss of prestress due to relaxation of steel is a time-dependent loss in prestress concrete. It is due to the reduction of stresses in steel with respect to time at constant strain. It generally depends upon the type of steel, age of member, initial stress in steel and type of exposure.

2. NUMERICAL STUDY

The cross section of beam is 100 mm wide and 150 mm deep. The length of beam is 1200 mm. Total 6 beams are used for prestress losses analysis. The Prestressing strand is made up of 3 high tensioned wires of size 3mm each. The beams are divided into 2 categories on basis of number of strands placed in the beams. There are 3 beams with single strand and 3 beams with double strands. The cable profile is parabolic in nature with maximum eccentricity of 50 mm at mid-span of beam and minimum eccentricity of 0 at supports of beam

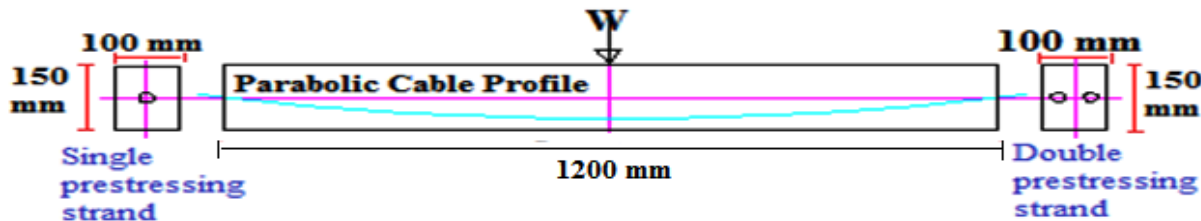


Fig 1: Cross-Sectional Details of Beams

The data available for the prestressed concrete beams,

- Characteristic concrete cube strength, $f_c = 35 \text{ N/mm}^2$
- Length of Beam, $L = 1200 \text{ mm}$; Width = 100 mm; Depth, $D = 150 \text{ mm}$
- Area of concrete section, $A = 15000 \text{ mm}^2$; Area of steel, $A_s = 21.2 \text{ mm}^2$
- Eccentricity, $e = 50 \text{ mm}$ (at midspan); 0 mm (at support)
- Modulus of Elasticity of Steel, $E_s = 2 \times 10^5 \text{ MPa}$
- Modulus of Elasticity of Concrete = $2 \times 10^4 \text{ MPa}$
- Modular Ratio, $m = 10$
- Section modulus at top fiber, $V_t = 75 \text{ mm}$
- Section Modulus at Bottom fiber, $V_b = 75 \text{ mm}$
- Second moment of area, $I = 28.125 \times 10^6 \text{ mm}^4$
- Self-weight of beam = 0.375 kN/m
- Max. Bending Moment at mid-span = 0.0675 kN-m

Table 1: Computational Details for Beams

Name of BEAMS	Prestress Force (kN)	No. of Strand	Area of concrete mm ²	Area of Steel mm ²	Stress in Tendons N/mm ²	Stress in Concrete N/mm ²	Second modulus I=bd ³ /12
P-1	36.10	1	15000	21.2	1702.80	5.48	28.125 × 10 ⁶
Q-1	37.30	1	15000	21.2	1759.40	5.67	28.125 × 10 ⁶
R-1	38.20	1	15000	21.2	1801.80	5.81	28.125 × 10 ⁶
P-2	60.00	2	15000	42.4	1415.10	9.21	28.125 × 10 ⁶
Q-2	62.20	2	15000	42.4	1466.98	9.55	28.125 × 10 ⁶
R-2	64.40	2	15000	42.4	1518.86	9.90	28.125 × 10 ⁶



Fig 2: Prestressed concrete beams

Prestress loss due to friction in the cable duct are calculated using following expression,

$$P_L = P_i [1 - (k \cdot x - \mu \cdot \alpha)]$$

The coefficient of wobble effect, k is taken as 15×10^{-4} for normal conditions. The frictional coefficient is taken as 0.3 as per IS Code 1343-2012. The commulative angle, α depends upon the jacking style, for both side jacking simultaneously it is taken as $4e/L$.

The value k depends on the type of jacking style. If the jacking is done from both ends simultaneously than the maximum effect or loss of prestress due to friction will take place at mid-span, Therefore, the value of k is taken as $L/2$.

Prestress loss due to anchorage slip in post tensioned prestressed concrete beams is shown as,

$$P_L = (\delta l / L) E_s$$

Anchorage slip, δl is taken as 0.75 mm. The magnitude of slip depends upon the type of wedge and the stress in the wires. This loss of prestress occurs only in post-tensioned members as no anchorages are used in pre-tensioned members.

Loss of prestress due to creep in post-tensioned prestressed concrete beam, as follow,

$$P_L = \phi \times m \times f_c$$

The Creep coefficient, ϕ is taken as 1 and modular ratio, m is 10. To evaluate the stress in concrete at level of tendon, the following equation is used,

$$f_c = [(P/A) + (P.e^e/I) - (M.e/I)]$$

The loss of prestress due to creep of concrete is obtained as the product of the modulus of elasticity of the prestressing steel and the ultimate creep strain of the concrete fibre integrated along the line of center of gravity of the prestressing steel over its entire length.

Loss of prestress in post-tensioned prestressed concrete beam due to shrinkage of concrete

$$\epsilon_s = 0.0002 / \log_{10} (t + 2)$$

The age of concrete at transfer in t days and shrinkage of concrete shall be the product of the modulus of elasticity of steel and the shrinkage strain of concrete.

Loss of prestress in post-tensioned prestressed concrete beam due to relaxation of steel. The relaxation losses in prestressing steels vary with type of steel, initial prestress, age, and temperature and, therefore, shall be determined from experiments. It is taken as 3% of initial stress.

3. RESULTS

The total losses calculated for the post-tensioning prestressed concrete beams using IS Code 11343:2012 are shown in table 2. The amount of prestress left in the post tensioned beams is shown in figure 3. The percentage prestress loss is higher in post tensioned beams having double strands than post tensioned beams having single strand, as shown in table 3.

Table 2: Loss of Prestress in Beams due to various factors

Name of Beams	Initial Prestress N/mm ²	Loss due to Friction	Loss due to Anchorage slip	Loss due to Creep	Loss due to Shrinkage	Loss due to steel Relaxation	Total Loss of Prestress N/mm ²
P-1	1702.80	85.14	125	54.8	40	51.06	356.00
Q-1	1759.40	87.97	125	55.9	40	52.78	361.65
R-1	1801.80	90.09	125	58.2	40	54.05	367.34
P-2	1415.10	70.75	125	92.1	40	42.45	370.30
Q-2	1466.98	73.35	125	95.5	40	44.00	377.85
R-2	1518.90	75.94	125	99.0	40	45.56	385.50

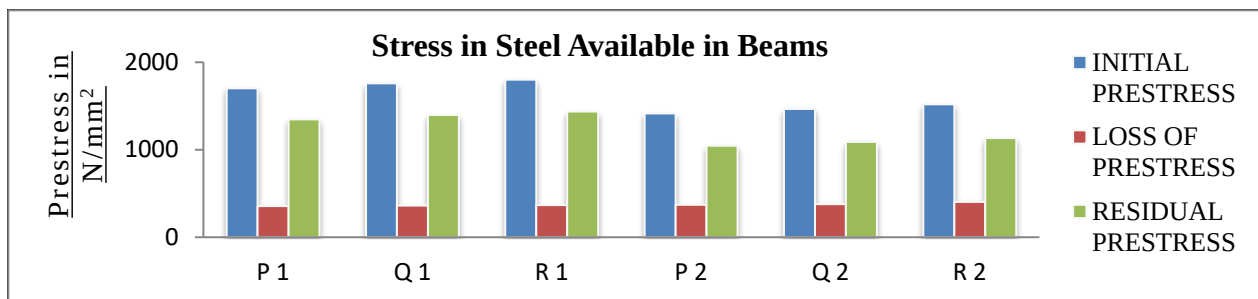


Fig 3: Initial Prestress, Loss of Prestress and Residual Prestress in Steel wires

Table 3: Remaining Prestressing Force in Beams and Percentage loss of Prestress in Beams

Name of Beams	Applied Prestressing Force in kN	Initial Prestress in N/mm ²	Total Loss of Prestress in N/mm ²	Residual Prestress in N/mm ²	Remaining Prestressing Force in kN	Percentage Loss of Prestress %
P-1	36.10	1702.80	356.00	1346.80	28.55	20.90
Q-1	37.30	1759.40	361.65	1397.75	29.63	20.55
R-1	38.20	1801.80	367.34	1434.46	30.41	20.38
P-2	60.00	1415.10	370.30	1044.80	44.29	26.16
Q-2	62.20	1466.98	377.85	1089.13	46.17	25.75
R-2	64.40	1518.90	385.50	1133.40	48.05	25.38

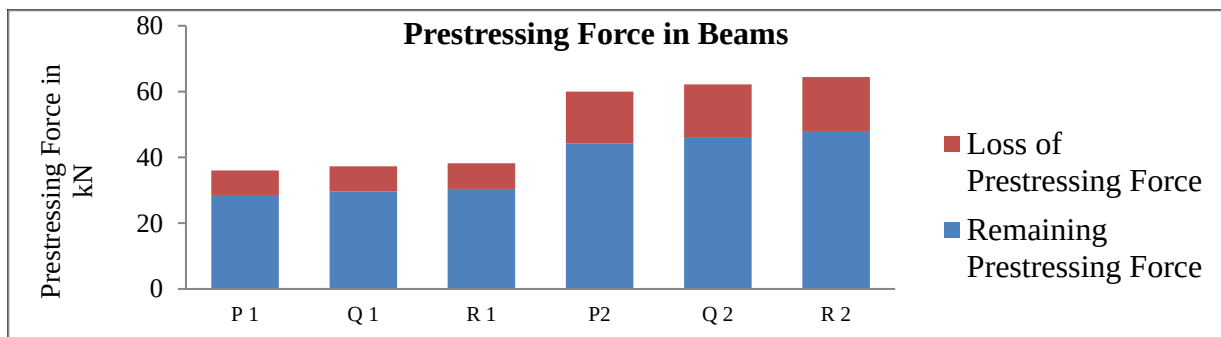


Fig 4: Initial Prestressing Force and Remaining Prestressing Force in Beams

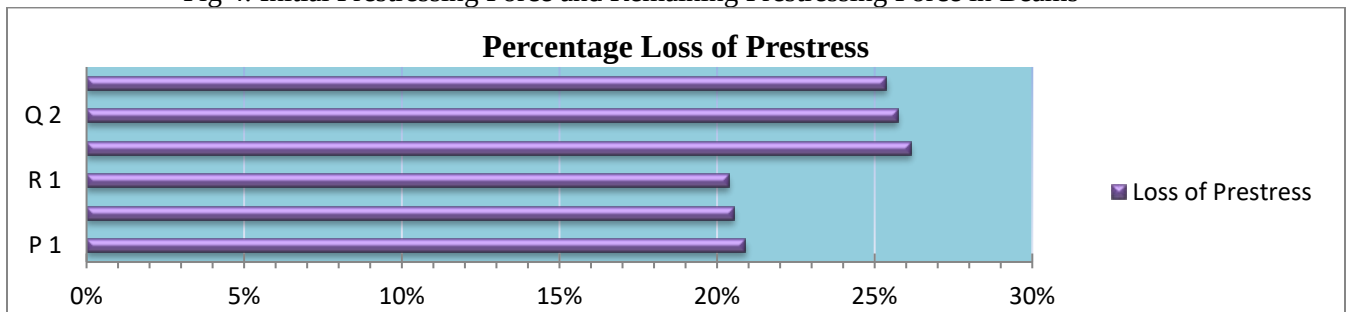


Fig 5: Percentage Loss of Prestress in Beams

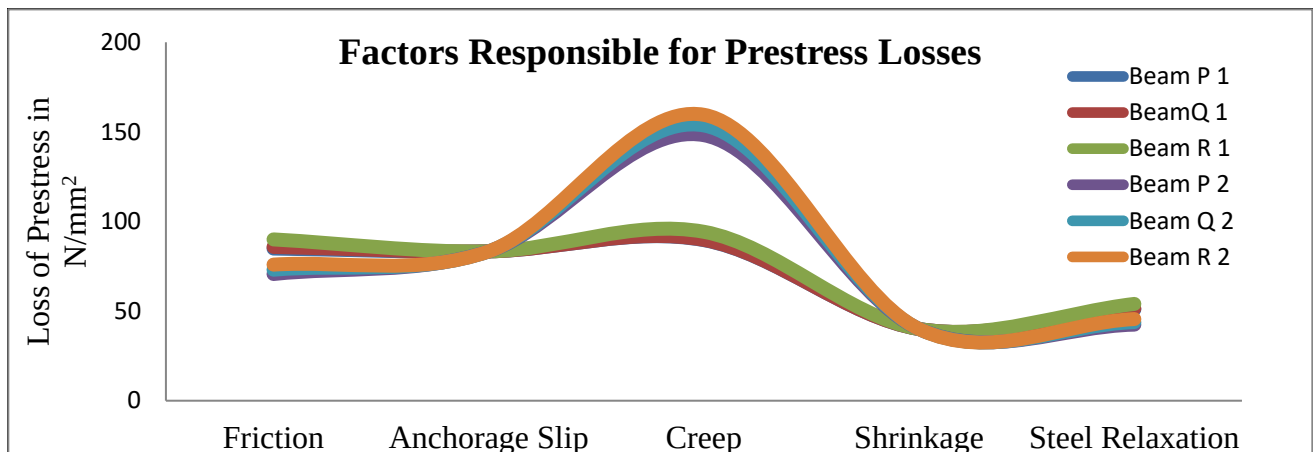


Fig 6: Comparison of Factors responsible for Losses in Prestressed Concrete Beam

4. CONCLUSION

The following points are concluded from present study,

- The maximum prestress loss in magnitude is seen in prestressed concrete beam with double prestressing strand R-2. However, the maximum percentage loss in prestress came in prestressed concrete beam with double prestressing strand P-2.
- Minimum loss of prestress loss in magnitude is seen in prestressed concrete beam with single prestressing strand P-1 whereas the maximum percentage loss of prestress came in prestressed concrete beam with single prestressing strand R-1.
- The Loss of prestress in prestressed concrete beams due to creep factor appear to be more in beams with double prestressing strands with similar cross-sectional area. However, the prestressing force is more in these beams. It gives value of creep which is independently of relative of humidity or volume to surface ratio. Rate of creep is, in turn, altered by the change in tendon stress.
- The rate of loss due to one factor, such as relaxation of tendons, is continually altered by changes in stress due to other factors such as shrinkage and creep of concrete.
- The Loss of prestress in prestressed concrete beams due to friction appear to be more in beams with double prestressing strands with similar cross-sectional area due to the effect of friction on both sides.
- If we consider that only one duct is placed in both groups so the actual effect of frictional loss is evaluated. The study suggests that more the magnitude more is the loss in prestress.
- Many of these factors are further dependent upon such uncertainties as material properties, time of loading, method of curing of concrete, environmental conditions and construction details. From above points it is therefore concluded that it is better to have one HDPE duct for cable comprising of many steel wires than multiple ducts for individual wires or group of wires.

5. REFERENCES

- 1 Bonopera, M. and Zanaty, A. 2020. "State of the art review on determining prestress losses in prestressed concrete girders." *Applied Sciences*, 10, 1-14.
- 2 Caro, L., Vargas, J. and Serna, P. 2013. "Prestress losses evaluation in prestressed concrete prismatic specimens." *Engineering Structures*, 48, 704-715.
- 3 Guo, T., Chen, Z., Lu, S. and Yao, R. 2018. "Monitoring and analysis of long-term prestress losses in post-tensioned concrete beams." *Measurement*, 122, 573-581.
- 4 Halvonik, J. and Dolnak, J. 2013. "Long-term losses of prestress in precast members cast from HPC." *Procedia Engineering*, 65, 81-86.
- 5 Marciukaitisa, G. and Jukneviciusa, L. 2017. "Deviation in deflections of eccentrically prestressed reinforced concrete structures." *Procedia Engineering*, 172, 706-710.
- 6 Moawad, M., El-Karmoty, H. and Zanaty, A. 2018. "Behavior of corroded bonded fully prestressed and conventional concrete beams." *HBRC Journal*, 14(2), 137-149.
- 7 Paez, P. and Sensale, B. 2018. "Improved prediction of long-term prestress loss in unbonded prestressed concrete members." *Engineering Structures*, 174, 111-125.
- 8 Warner, R. 2015. "Analysis of shrinkage in prestressed concrete slabs and beams." *Australian Journal of Structural Engineering*, 15(2), 151-159.
- 9 Wei, Y., Zhang, L., Au, F., Li, J. and Tsang, N. 2016. "Thermal creep and relaxation of prestressing steel." *Construction and Building Materials*, 128, 118-127.
- 10 Bureau of Indian Standards. IS 1343-2012, Prestressed Concrete-Code of Practice (Second Revision) Bureau of Indian Standards: New Delhi, 2012.

Retrofitting of reinforced concrete beams using self-compacting concrete as jacketing material: A state-of-the-art review

Ankur Verma¹, Dr. A. Mahesh Babu², Dr. Rajesh Bhargava²

Ankur Verma, Research Scholar, Department of Civil Engineering, PK University, Shivpuri, India

Dr A. Mahesh Babu, Professor, Department of Civil Engineering, PK University, Shivpuri, India

Dr Rajesh Bhargava, Deputy Registrar, RGPV, Bhopal

ABSTRACT

In this paper, the overall review about the change in strength parameters and ductility behaviour of reinforced concrete beams is discussed when reinforced concrete beams are strengthened with self-compacting concrete jacketing. The purpose of self-compacting concrete jacketing is to increase the strength of existing structural members to strengthen the damaged structural members or due to increase in service load on structural members. Various reasons causing damage to structural members are design errors, faulty construction, earthquakes, accidents, fire etc. Self-compacting concrete jacketing is used for repair and rehabilitation of damaged structural members. The discussion includes effectiveness of self-compacting concrete as jacketing material for overall enhancement of structural members.

Keywords: Retrofitting, Jacketing, Reinforced Self-Compacting Concrete, Fibre Reinforced self-compacting concrete, Steel wire mesh

corresponding author (e-mail: ankurverma2019@gmail.com)

I.INTRODUCTION

Self-compacting concrete is a special kind of concrete that can percolate and fill voids in places where heavy reinforcement is provided and also fill corners of mould completely without the use of vibrators for compaction during process of placing concrete in the mould. Self-compacting concrete is highly fluidic in nature and it is suitably placed in difficult conditions and in sections with congested reinforcement. The development of self-compacting concrete started keeping in mind lack of uniformity and necessity of compaction by vibration in concrete by University of Tokyo, Japan in late 1980's.

Self-compacting concrete can be placed faster without mechanical vibration and less screeding which course reduction in placement cost. It makes more uniform structural surface finish with little or no remedial surface work. Self-compacting concrete reaches areas easily and restricted sections can be filled completely. Difficult

structures and shapes can be obtained easily by using self-compacting concrete. It provides better consolidation around reinforcement. Self-compacting concrete have better pumping ability. It gives high labour saving, cost saving by reducing the construction period. Easily placed in thin-walled elements with limited access. As skills of workers, the shape and amount of reinforcement bars or the arrangement of structures does not affect self-compacting concrete because of its high fluidity and resistance to segregation it can also be pumped to longer distance. The elimination of vibration leads to an improved concrete quality, decreased skilled labour and shortens the time needed for construction. It possesses the ability to moulded into any shape with the help of mould. It is used in congested areas where compaction equipment's cannot be used. Thus, reducing the cost of the structure to about one tenth of the total cost of structure.

Beams are one of the most important structural members which transfers the loads to the columns. The behaviour of beam in structures is very important since beam failures lead to structural failures. Replacement of the damaged structural elements is very difficult and may create a high risk to the overall structural integrity. Jacketing of a beam is needed when the load carried by the member is increased or due to mistakes in the design. Conventional retrofitting techniques, such as concrete and steel jacketing, have been used significantly for the repair and rehabilitation of reinforced concrete structures. The aim of this paper is to have a comprehensive literature review of the work done in the field of self-compacting concrete in order to get a better idea of the issues relevant to strengthening of reinforced concrete beams with self-compacting concrete used as jacketing material.

II. LITERATURE REVIEW

Constantin E. Chaliors et al (2012) [1] conducted a study for rehabilitation of shear damaged reinforced concrete beams using self-compacting concrete jacketing. Damaged beams were restored using reinforced self-compacting concrete and tested using 4-point loading system. Calculation is made on flexural strength and shear strength of strengthened tested beams. Evaluation of yield capacity and ultimate load capacity of jacketed beams is done.

Constantin E. Chaliors et al (2012) [2] deals with tests and analysis of self-compacting concrete jacketing for strengthening of shear damaged reinforced concrete beams. U-shape jacketing is provided to damaged beams to increase shear capacity of original beams. The strengthened beams are tested under four-point loading system. Test result shows ductile failure of strengthened beams and increase in overall performance of strengthened RC beams indicating efficiency of self-compacting concrete jacketing.

Constantin E. Chaliors (2013) [3] investigates efficiency of reinforced self-compacting concrete as jacketing material for retrofitting of damaged reinforced concrete beams under monotonic and repeated loading.

Experimental study included 12 beams. The size of beams is 1600 mm × 125 mm × 200 mm. U-form jacketing style has been used with small diameter steel bars and self-compacting concrete. The compressive strength and tensile strength of self-compacting concrete is 40.10 MPa and 3.5 MPa respectively. Result shows increase in load carrying capacity of jacketed beams by 35 to 50%. The ultimate shear load varies between 39.7 kN to 42.0 kN. All jacketed beams fail in ductile manner showing flexural response whereas original beams show brittle response at failure. This study concludes that use of reinforced self-compacting concrete as jacketing material for restoration and rehabilitation of damaged reinforced concrete beams is effective and reliable.

Constantin E. Chaliotis (2014) [4] presents effective use of reinforced self-compacting concrete for repair and strengthening of under designed reinforced concrete beams. Experimental program consists of 20 RC beams. The beams are tested near failure and then strengthened. Result shows thin layered self-compacting concrete jacketing provide better structural performance than normal concrete jacketing. Full recovery of damaged RC beams due to previous loading with increase in strength and enhanced ductility capacity. The paper concludes that use of reinforced self-compacting concrete is an excellent methods for repair and rehabilitation for earthquake damaged structures.

Klaus Holschemacher et al (2017) [5] evaluates the use of steel fibre reinforced high strength light weight self-compacting concrete as jacketing material for strengthening of reinforced concrete beams. Result shows increase in peak load capacity is in range of 14% to 58% with 40 mm, 50 mm and 60 mm layers of steel fibre reinforced high strength light weight self-compacting concrete for strengthening of reinforced concrete beams. Application of steel fibre reinforced high strength light weight self-compacting concrete in tension zone of beam increases peak load by 33.1% and significant increase in stiffness of strengthened beams.

Xuhui Zhang et al (2018) [6] deals with strengthening of damaged reinforced concrete T-beams using self-compacting concrete as jacketing material. Experimental program consists of 8 reinforced concrete T-beams which are subjected to loading near failure and then strengthened using self-compacting concrete as jacketing material and test of strengthened beams conducted for flexural strength. Result shows enhancement in performance of strengthened beams in terms of flexural strength and stiffness. The flexural load capacity of strengthened reinforced concrete beams by using self-compacting concrete as jacketing material is being twice of flexural load capacity of initial reinforced concrete beams without any jacketing.

Abhilash CS et al (2019) [7] investigates the use of self-curing self-compacting concrete as a jacketing material for retrofitting of RC beams. In this paper, cement is being replaced by flyash and alcofine at varied proportions by weight of cementitious material. The size of RC beam is 2800 mm × 150 mm × 300 mm. RC beams of 150mm X 250mm X 2000 mm overall and 150mm X 219mm X 2600mm effective will be casted. with different reinforcing conditions. The mechanical properties are evaluated at 3,7,28,56,90 days. Slump flow test, L-box

test, V-funnel test are conducted to check the quality of concrete as per set parameters. Several tests conducted for determining strength of hardened concrete such as compression test, split tensile test, acid attack and sulphate attack. Linear variation deflection transmission (LVDT) was used to note down the deflections of the test beams at three positions. One below mid- span and other two below the loading points. Result analysis is done on load carrying capacity of strengthened beams. Self-compacting concrete mix improves the flowability properties with increased rheology in terms of slump flow, V-Funnel and L-Box. It is concluded that to achieve better rheological properties of self-compacting concrete, Fly ash can be used as secondary cementitious material and Alcolfine as tertiary cementitious material in self-compacting concrete. The rate of strength development in Partially replaced concrete will be very slow at 3rd days and 7th day due to pozzalonic behaviour.

Mohamed Abu A. Maraq et al (2020) [8] presents flexural behaviour of reinforced concrete beams strengthened with steel wire mesh and self-compacting concrete. Experimental program consists of 18 RC beams, designed as per American building code ACI318. The size of control beam is 1200 mm × 150 mm × 100 mm and size of monolithic control beams and jacketed beams is 1200 mm × 200 mm × 160 mm. Out of 18 RC beams, 3 RC beams are used as control beams specimen, 4 are used as monolithic control beams specimen and rest 11 RC beams are used as jacketed beams specimen. The jacketed beams are further divided into group A and group B. Group A and group B jacketed beams are subjected to 110% and 163% load carrying capacity of control beams respectively, before its restoration using steel wire mesh and self-compacting concrete. Result shows use of steel wire mesh along with self-compacting concrete increase load carrying capacity, ductility, stiffness and cracking load of beams with respect to conventional beams. Reinforcement ratio of galvanised steel wire mesh increased in group B, and therefore the flexural recovery of strengthened beams of group B is more than group A. The paper concludes utilization of steel wire mesh and self-compacting jacketing is an efficient technique to strengthen RC beams in flexure.

Hamed Shabani Attar et al (2020) [9] analysis flexural and shear strengthening of reinforced concrete beams using fibre reinforced self-compacting concrete as jacketing material. Experimental program consists of 10 RC beams which are categorised into group A and group B. In group A beams, shear strength of strengthened beams is evaluated whereas in group B beams, flexural strength of strengthened beams is examined by providing high amount of shear reinforcement in this group. The study uses different variables in terms of steel fibre dosage, shear reinforcement, GFRP rebars and longitudinal ratios for all strengthened beams. Result shows failure mode changes to flexure in group B beams. The beams which are strengthened with GFRP rebars for flexural strengthening shows combination of shear and flexural modes at failure.

Nuroji et al (2020) [10] deals with behaviour of reinforced concrete beams after jacketing using self-compacting concrete. Experimental investigation includes casting of control beam having size 125 mm × 200

mm with M20.3 grade of concrete and strengthened beam having size 200 mm × 300 mm with M23.9 grade of concrete. Beams are tested under two-point loading system. Result shows that sectional enlargement of strengthened beams increases load carrying capacity and stiffness of beams. Moment capacity of strengthened beams becomes six times more than capacity of control beams. Stiffness performance of strengthened beams becomes seven times more than performance of control beams.

Iraj Rahmani et al (2020) [11] studies the effect of steel fibre reinforced self-compacting concrete as a jacketing material for strengthening of reinforced concrete beams. Experimental program consists of 25 RC beams having variables in type of concrete, grade of concrete, use of reinforcement bars and steel fibres. Strengthened beams are tested under three-point loading system in terms of load-displacement values. Result shows increase in load bearing capacity of strengthened beams by 7.4 times to reach yield load and 5.1 times to reach ultimate load. The result also concludes that combination of steel fibres and steel bars reduces cracks and create better bonding between reinforcement and concrete. Concentration of cracks appeared in middle of span and there is reduction in rate of increase in crack length due to better distribution of stress.

Bassam A. Tayeh et al (2020) [12] investigates use of self-compacting concrete and steel welded wire mesh for strengthening of reinforced concrete beams. Experimental program consists of 3 control beams, 4 monolithic beams and 11 strengthened beams. Strengthened beams are divided into two groups on basis of steel wire mesh and bonding techniques. Result shows that strengthening techniques improves flexural capacity of strengthened beams.

K. Rajesh Kumar et al (2021) [13] evaluates the structural performance of fibre reinforced self-compacting concrete as jacketing material for strengthening of corroded reinforced concrete beams. Experimental investigation includes beams having size 700 mm × 100 mm × 300 mm. Glass chopped fibres and polypropylene fibres are used as steel reinforcement in self-compacting concrete and their compressive strength, flexural strength, mechanical properties are evaluated. Result findings show use of fibre reinforced self-compacting concrete in strengthening of RC beams don't show any harmful effect on structural properties. Result concludes that use of glass fibre in self-compacting concrete increases compressive strength by 0.06% and flexural strength by 15.4 % whereas use of polypropylene fibre in self-compacting concrete increases compressive strength by 0.1% and flexural strength by 40.8% in comparison to plain self-compacting concrete used as jacketing materials for strengthening of reinforced concrete beams. Structural performance of strengthened RC beams is enhanced in terms of flexural load capacity, stiffness, ductility and ultimate energy because of using fibre reinforced self-compacting concrete as jacketing material.

III. CONCLUSION

On the basis of results obtained from various literatures mentioned in this study, the conclusion made is that self-compacting concrete jacketing leads to a uniformly distributed increase in strength and stiffness of RC beams. The load carrying capacity of RC beams strengthened with self-compacting concrete jacketing is higher than RC beams strengthened with normal concrete. Significant improvement in durability of damaged beams and increase in total stiffness of beams. No sign of delamination is been seen in strengthened specimens between existing concrete and self-compacting concrete. Use of dowel bars, connectors enhance the bond between existing concrete and self-compacting concrete. Fibre reinforced polymers used as reinforcement in self-compacting concrete enhances the strength, ductility, and energy absorption capacity of strengthened RC beams. The self-compacting concrete used as jacketing material is efficient and effective technique that can withstand large axial load and impart high ductility.

Table 1: Summary of studies on strengthening of reinforced concrete beams using self-compacting concrete jacketing

S/N	Study	Jacketing material	Effect on ductility	Effect on strength	Effect on stiffness
1	C. E. Chalioris et al [1]	SCC	Increased	Significantly Increased	Increased
2	C. E. Chalioris et al [2]	SCC	Increased	Significantly Increased	Increased
3	C. E. Chalioris et al [3]	SCC	Increased	Significantly Increased	Increased
4	C. E. Chalioris et al [4]	SCC	Increased	Significantly Increased	Increased
5	K. Holschemacher et al [5]	SFR-HS-LW-SCC	Highly Increased	Highly Increased	Highly Increased
6	Xuhui Zhang et al [6]	SCC	Increased	Increased	Increased
7	Abhilash CS et al [7]	SC-SCC	Increased	Significantly Increased	Increased
8	Mohamed Maraq et al [8]	SWM-SCC	Highly Increased	Increased	Increased
9	Hamed S. Attar et al [9]	FRP-SCC	Highly Increased	Highly Increased	Increased
10	Nuroji et al [10]	SCC	Significantly Increased	Significantly Increased	unchanged
11	Iraj Rahmani et al [11]	SFR-SCC	Highly Increased	Highly Increased	Increased
12	Bassam A. Tayeh et al [12]	SWM-SCC	Significantly Increased	Highly Increased	unchanged
13	K. Rajesh Ku et al [13]	FRP-SCC	Highly Increased	Highly Increased	Increased

IV. ACKNOWLEDGMENT

I would like to express a deep sense of gratitude to all the scholars, authors and publishers whose articles and journals are cited and from that valuable data was reviewed and discussed for completing this review paper.

V. REFERENCES

- [1] C. E. Chalioris and C. N. Pourzitidis, "Rehabilitation of Shear-Damaged Reinforced Concrete Beams using self compacting concrete jacketing," *International Scholarly Research Network* , 2012.
- [2] C. E. Chalioris and C. N. Pourzitidis, "Self-Compacting Concrete Jacketing – Tests and Analysis," in *AASRI Conference on Modeling, Identification and Control*, Xanthi, Greece, 2012.
- [3] C. E. Chalioris, C. P. Papadopoulou, C. N. Pourzitidis, D. Fotis and K. K. Sideris, "Application of a Reinforced Self-Compacting Concrete Jacket in damaged reinforced concrete beams under monotonic and repeated loading," *Journal of Engineering*, 2013.
- [4] C. E. Chalioris, G. E. Thermou and S. . J. Pantazopoulou, "Behaviour of rehabilitated RC beams with self-compacting concrete jacketing - analytical model and test results," *Construction and building materials* , vol. 55, pp. 257-273, 2014.
- [5] K. Holschemacher, . S. Iqbal, A. Ali and T. A. Bier, "Strengthening of RC beams using lightweight self-compacting cementitious composite," in *Modern Building Materials, Structures and Techniques*, Frieberg, Germany, 2016.
- [6] X. Zhang, Y. Luo, L. Wang, J. Zhang, W. Wu and . C. Yang, "Flexural strengthening of damaged RC T-beams using self-compacting concrete jacketing under different sustaining load," *Construction and building materials*, vol. 172, pp. 185-195, 2018.
- [7] A. C S and S. K. Tengali, "Retrofitting of RC beams using self curing self compacting concrete," *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 2, pp. 550-553, 2019.
- [8] M. . A. A. Maraq, B. . A. Tayeh, M. M. Ziara and R. Alyousef, "Flexural behavior of RC beams strengthened with steel wire mesh and self compacting concrete jacketing-experimental investigation and test results," *Journal of material research and technology*, vol. 10, pp. 1002-1019, 2020.
- [9] H. S. Attar, M. . R. Esfahani and A. Ramezani, "Experimental investigation of flexural and shear strengthening of RC beams using fibre reinforced self consolidating concrete jackets," *Structures*, vol. 27, pp. 46-53, 2020.

- [10] N. C.-C. Hung, B. H. Prasetya and A. Han, "The Behavior of Reinforced Concrete Members with sectional enlargement using self compacting concrete," *International review of civil engineering*, vol. 11, 2020.
- [11] I. Rahmani, A. Maleki and M. A. Lotfollahi-Yaghin, "A Laboratory Study on the Flexural and Shear Behavior of RC Beams retrofitted with steel fibre reinforced self compacting concrete jacket," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 2020.
- [12] B. . A. Tayeh, M. A. A. Maraq and M. M. Ziara, "Flexural performance of reinforced concrete beams strengthened with self compacting concrete jacketing and steel welded wire mesh," *Structures*, vol. 28, pp. 2146-2162, 2020.
- [13] K. R. kumar, G. Shyamala and A. Adesina, "Structural performance of corroded reinforced concrete beams made with fibre reinforced self compacting concrete," *Structures*, vol. 32, pp. 1145-1155, 2021.

The study is relevant to the theme "engineering and technology" of Shodh Shikhar research festival as the research paper is related to latest technology and materials used in repair and rehabilitation of damaged structures in the field of civil engineering. The paper discusses the comprehensive literature review of the work done in the field of strengthening structural members with use of self-compacting concrete.



RNTU

Rabindranath
TAGORE
UNIVERSITY™

Organizes



International Research Paper & Project Symposium

24th - 25th Feb, 2023

Certificate of Presentation

This is to certify that Mr./Ms/Dr. Ankur Verma College/
University has presented
Research Paper / Project in International Research Paper and Project Symposium-Shodh
Shikhar 2023 on the topic Retrofitting of Reinforced Concrete beams using Self-Compacting Concrete as
Jacketing Material: A State-of-the-art review
held on 24th -25th Feb. 2023 at Rabindranath Tagore University, Bhopal (M.P.)

Dr. Bramh Prakash Pethiya
Vice Chancellor, RNTU

Dr. Vijay Singh
Registrar, RNTU

Dr. Shalini Yadav
Convener



CORPORATE INSTITUTE OF SCIENCE AND TECHNOLOGY, BHOPAL

International Conference on “Recent Trends in Multidisciplinary Innovations”

30th November to 2nd December 2023



Sponsored by

CERTIFICATE

We hereby certify that Dr. P. Prof. Ankur Verma has delivered an
of

Invited Talk / Chaired a session / Presented a paper / Participated entitled
Experimental Study of modified M20 concrete with Waste Plastic
Polystyrene Cubes.
in the above conference.


Director,
Dr. Bharat Kishore Gupta


Organizing Secretary

Convener,
Dr. B Suresh