# STUDY OF REPAIRED AND STRENGTHENED RC BEAMS USING DIFFERENT JACKETING TECHNIQUES

By

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# STUDY OF REPAIRED AND STRENGTHENED RC BEAMS USING DIFFERENT JACKETING TECHNIQUES

**Major Project**

Submitted in partial fulfillment of the requirements

For the degree of

**Master of Technology in Civil Engineering**

By


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**AHMEDABAD-382481**

**May 2012**

# Declaration

This is to certify that

i) The thesis comprises my original work towards the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) at Nirma University and has not been submitted elsewhere for a degree.

ii) Due acknowledgement has been made in the text to all other material used.

**Sachin S. Raval**

# Certificate

This is to certify that the Major Project entitled "Study of Repaired and Strengthened RC Beams using different Jacketing Techniques" submitted by Mr. Sachin S. Raval (10MCLC13), towards the partial fulfilment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) of Nirma University of Science and Technology, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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Date of Examination

# Abstract

Strengthening of Reinforced Concrete (RC) beams is required due to design errors, deficient concrete production, bad execution processes, damage due to earthquake, an accident, such as collisions, fire, explosions and situations involving changes in the functionality of the structure etc. It is known that many buildings designed based on older codes may be susceptible to serious damage during such accidents. Older buildings have been structurally designed for much lower load carrying capacity as compared to that of buildings which are designed today. Structural rehabilitation brings a structure or a structural member to a specified safety and performance level. Depending on state of a structure or a structural member, rehabilitation can be divided into two categories: Repair and Strengthening. Repair is the rehabilitation of a damaged structure or a structural member, on the other hand strengthening is upgrading an undamaged structure or the member. Various methods for strengthening of RC beams are being employed in practice. Jacketing has been considered as one of the important methods for strengthening and repairing of RC beams. Jacketing is done by enlarging the existing cross section with a new layer of concrete that is reinforced with both longitudinal and transverse reinforcement.

Total eighteen RC beams of size 150mm x 300mm x 2.1m span have been cast. Eight beams are considered for strengthening. Other eight beams are considered for repairs and strengthening. Remaining two beams are considered as control beams. Four beams from each strengthened and repaired and strengthened category have been kept as-cast with smooth surface. Surface of remaining four beams from each strengthened and repaired and strengthened category has been chipped for about 10-15mm from all the sides.

Eight strengthened beams have been jacketed using additional reinforcement for 60mm thickness all-round. For eight repaired and strengthened beams, all beams

are loaded up to its failure and repaired by means of grouting. For checking effectiveness of grouting for filling up of cracks, Ultrasonic pulse velocity test is conducted on all grouted beams. After grouting, increment in pulse velocity of grouted beams has been observed as compared to non-grouted. The jacketing is executed for all beams after grouting. Jacketed beam cross-section is considered as 270mm x 420mm. Four different methods have been employed for jacketing of RC beams in the present investigation. These methods include use of dowel connectors and micro-concrete, bonding agent and micro-concrete, combined use of dowel connectors, bonding agent and micro-concrete and without dowel connectors, bonding agent and use of only micro-concrete. All four methods have been employed for jacketing of the beams with the smooth as well as the chipped surface.

RC beams have been tested with two point loading. Comparative performance of strengthened and repaired and strengthened beams has been evaluated. Failure load, displacement at mid span and below the point load, strain variation in concrete at different locations, failure modes and crack pattern has been evaluated for all the beams. Most effective techniques of jacketing for strengthening of RC beams with different surfaces has been evaluated. Comparative assessment has been done on the effectiveness of each type of method of jacketing RC beams with smooth and chipped surfaces.

For smooth surface strengthened beams and repaired and strengthened beams, higher load caring capacity, higher displacement and higher strain has been observed for beam with combined use of dowel connectors, bonding agent and micro-concrete. For smooth surface repaired beams and strengthened and strengthened beams, higher experimental load has been observed for same beam as compared to that for analytical load.

For chipped surface strengthened beams and repaired and strengthened beams, higher load caring capacity, higher displacement and higher strain has been observed for beam with only micro-concrete without dowel connectors, bonding agent. For smooth surface repaired beams and strengthened and strengthened beams, higher experimental load has been observed for same beam as compared to that for analytical load.

For all strengthened and repaired and strengthened beams load carrying capacity evaluated is within range of 1.69 % to 16 %. It has been observed that when requirement of change in utility of structure occurs, strengthening by jacketing is more suitable. For fully damaged structure, repairing by grouting and strengthening by jacketing is more suitable. For smooth surface beam jacketing method of combined use of dowel connectors and bonding agent with micro-concrete is more advantageous in term of bond between old to new concrete. For chipped surface beam jacketing method of using only micro-concrete without dowel connectors and bonding agent gives good bond between old to new concrete.

# Acknowledgements

I cannot present this work without first expressing my appreciation and gratitude to **Dr. Urmil V. Dave**, for their valuable guidance and constant encouragement at every stage of progress of the major project work. It was a very pleasant and inspiring experience for me to work under them.

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I am thankful to my parents who have change their priorities according to my needs and taught me the basic principles of life. I am also thankful to my wife who has given me great support during my experimental work.

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**Sachin S. Raval**
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# Abbreviation, Notation and Nomenclature

$L$ ........ Span of beam

$b$ ........ Width of control beam

$b'$ ........ Width of jacketed beam

$D$ ........ Overall Depth of control beam

$D'$ ........ Overall Depth of jacketed beam

$d$ ........ Effective depth of control beam

$d'$ ........ Effective depth of jacketed beam

$f_{ck}$ ........ Characteristic compressive strength for control beam

$f_{ck'}$ ........ Characteristic compressive strength for jacketed beam

$f_y$ ........ Characteristic tensile strength of reinforcement steel

$A_{st1}$ ........ Area of tension reinforcement for control beam

$A_{st2}$ ........ Area of tension reinforcement for jacketed beam

$M_u$ ........ Ultimate moment

$P$ ........ Flexure load

$V_u$ ........ Shear force due to design loads

$\tau_v$ ........ Nominal shear stress

$V_{us}$ ........ Strength of shear reinforcrment

$\tau_c$ ........ Design shear strength of concrete

$\tau_{cmax}$ ........ Maximum shear stress

$S_v$ ........ Spacing of the stirrups along the length of beam

$Q$ ........ Strengthened Beam

$R$ ........ Repaired Beam

$C$ ........ Control Beam

$S$ ........ Beam with Smooth Surface and micro-concrete

$P$ ........ Beam with Chipped Surface and micro-concrete

$D$ ........ Beam with Dowel Connectors and micro-concrete

$B$ ........ Beam with Bonding Agent and micro-concrete

$M$ . . . Beam without Dowel Connectors and Bonding Agent and only micro-concrete

$X_u$ . . . Depth of neutral axis from top side of beams

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# Chapter 1

# Introduction

## 1.1 General

It is known that many buildings designed based on old codes were susceptible to serious damage during a large earthquake. Old buildings have been structurally designed for much lesser seismic actions when compared to buildings that are designed today. One popular solution to the problem of strengthening old reinforced concrete (RC) structures is to place jackets around the structural elements. Jackets have been constructed using concrete, steel elements, ?bre-reinforced polymer composites, and use of additional reinforcement. Depending on the state of the structure or the structural member, rehabilitation can be divided into two categories: Repair and Strengthening. Repair is the rehabilitation of damaged structure or structural member, whereas strengthening is upgrading an undamaged structure or member.

Jacketing is one of the most common techniques used for repairing and strengthening reinforced concrete elements. It is done by enlarging cross section with a new layer concrete that is reinforced with both longitudinal and transverse reinforcement. Several experimental studies have been performed in order to investigate the method. It has been shown that the method improves bending strength, shear capacity, sti?ness, ductility and axial load carrying capacity of strengthened elements.

## 1.2 Strengthening of RC beam

Several methods are used for strengthening of beam like concrete jacketing, steel jacketing, precast concrete jacketing, external prestressing and FRP wrapping. These methods are explained as follows:

- **Concrete Jacketing**

  Fig. 1.1 shows jacketed beam section. Concrete jacketing involves addition of a thick layer of RC in the form of a jacket, using longitudinal reinforcement and transverse ties. Additional concrete and reinforcement contribute to strength increase of section. General thickness of jacket is up to 100 mm. The stiffness of the system is highly increased due to jacketing. For beam section stirrups are required to be anchored in slab. For column longitudinal bars need to be anchored to the foundation and should be continuous through the slab. Jacketing requires drilling of holes in existing column, slab, beams and footings. After jacketing size, weight and stiffness of the column increase.

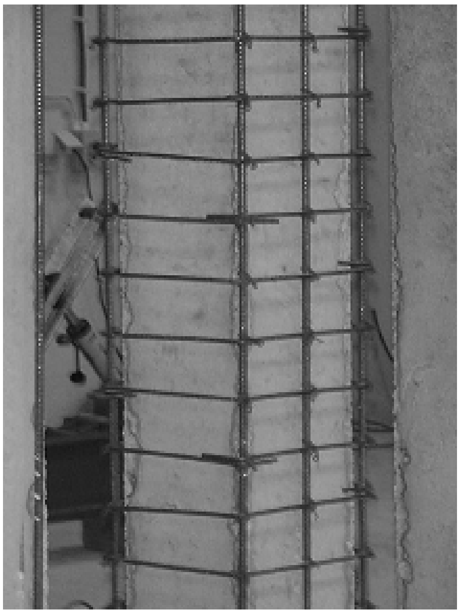


Figure 1.1: jacketed beam section

- **Steel jacketing**

  Fig. 1.2 shows steel jacketing. In steel jacketing encasing the column with steel plates and filling the gap with a non-shrink grout is carried out. Steel jacketing provides confinement to core concrete. Its high young's modulus causes the steel to take a large axial load. General thickness of grout is 25 mm. Steel jacket is affected by corrosion and impact with floating materials, so it is not used for columns in river, lake and seas.

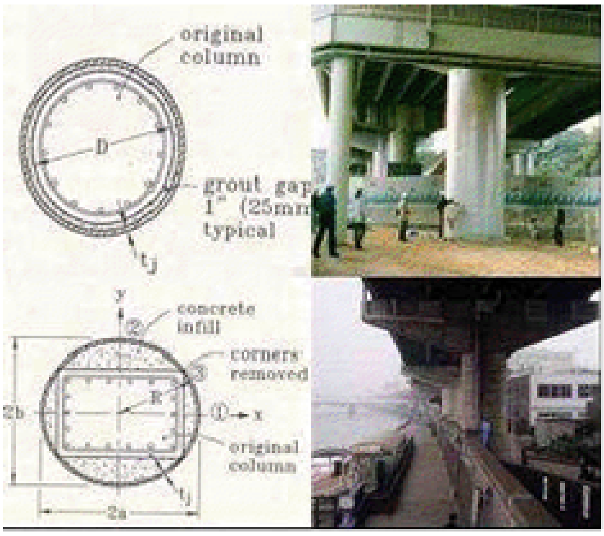



Figure 1.2: steel jacketing

- **Precast Concrete Jacketing**

  Fig. 1.3 shows Precast Concrete Jacketing. Construction process for precast concrete jacketing is faster. New longitudinal reinforcement is set around the existing column, and precast concrete segments are set around the new reinforcement in precast concrete jacketing. All segments are tied together by strands. After injecting non-shrinkage mortar between the existing concrete and precast concrete segment, prestressed force is introduced in the strands to assure the contact of the segments.

Figure 1.3: Precast Concrete Jacketing

- **External Prestressing**

  Fig. 1.4 shows External Prestressing. External Prestressing involves prestressing the columns by external strands to provide confinement. It is efficient and can be more economical than steel jacketing. Installation of such a system can be less disturbing to the building occupants. The technique is very recently developed and on-site implementation is not known.

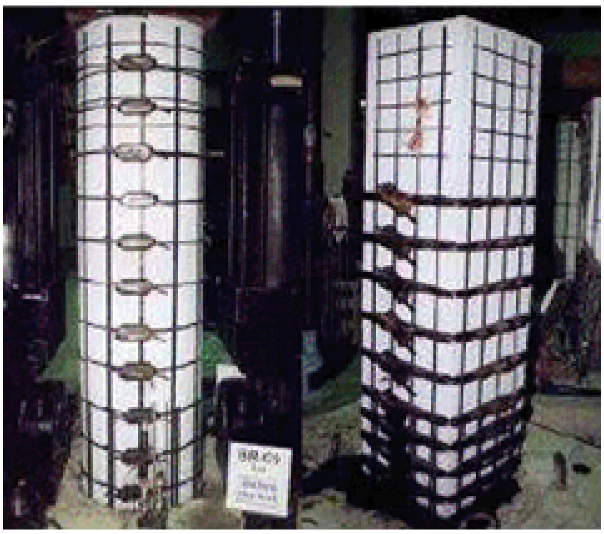


Figure 1.4: External Prestressing

- **FRP Wrapping**

  Fig. 1.5 shows FRP Wrapping of beam column junction. FRP Wrapping involves wrapping of RC beam and column by high strength-low weight fiber wraps to provide confinement, which increases both strength and ductility. FRP sheets are wrapped around the beams and columns, with fibers oriented perpendicular to the longitudinal axis of beam and column, and they are fixed to the element using epoxy resin. The wrap not only provides confinement and increases the concrete strength, but also provides significant strength against shear and flexure.

Figure 1.5: FRP Wrapping of beam column junction

## 1.3 Research Significance

The need to strengthen beams for any structure may arise at any time from the beginning of the construction phase until the end of the service life or when the structure is distressed. During the construction phase, the strengthening of beam may be required because of,

- Design errors
- Deficient concrete production
- Bad execution processes
- Situations involving changes in the structure functionality
- The development of more demanding code requirements

During the service life, the strengthening of beam in any structure may arise on account of,

- An earthquake or other such natural calamity
- An accident, such as collisions, fire, explosions, etc.
- Distress in structure due to various physical and chemical factors

To overcome above related to functionality of beam for any structure, jacketing using additional reinforcement may be carried out for its strengthening. Further, for the damaged beams during their service life, the repairing of beams may be carried out by grouting and the beams strengthening by jacketing.

Less amount of research has been performed on techniques for jacketing using dowel connectors alone, bonding agent alone, combined use of dowel connectors and bonding agent and without using dowel connectors and bonding agent on smooth and chipped surfaces of the beams. Also less amount of work has been done for comparing performance of strengthened and repaired and strengthened beams by jacketing. For above reasons the present work is aimed towards Study of Repaired and Strengthened RC beams using different jacketing Techniques for smooth and chipped surfaces.

## 1.4 Objectives of Study

To study various parameters, following objectives are decided for the major project.

1) To evaluate the response of RC beam subjected to flexure loading by measuring structural parameters such as ultimate load, failure load, maximum displacement, strain variation, failure shape, crack patterns, etc.

2) To study effectiveness of jacketing on the beam using additional reinforcement.

3) To study effectiveness of dowel connectors and micro-concrete, bonding agent and micro-concrete, combination of dowel connectors and bonding agent and micro-concrete and without dowel connectors and bonding agent and using only micro-concrete for jacketing of the beam.

4) To study the effectiveness of above method jacketing when the beam surface is smooth as well as chipped.

5) To evaluate effectiveness of grouting for damaged beams before jacketing.

6) To determine bond strength between old and new concrete for smooth surface and chipped surface of the beams.

7) To compare behavior of strengthened beams and repaired and strengthened beams for evaluating efficiency of the jacketing method in case of beams.

## 1.5 Scope of work

- Total eighteen RC beams of size 150mm x 300mmx 2100mm are to be cast in the laboratory. The c/s dimensions and span of the RC beams is to be selected based on information available from the literature survey.

- The beams are to be divided in two major categories.

- Category -I consists of eight RC beams. These beams are to be strengthened by jacketing. Out of these eight beams surface of four beams are to be kept as cast and surface of remaining four beams is to be chipped up to 10mm to 15mm all around the beams. Four different methods are to be employed for jacketing of RC beams using micro-concrete in the present investigation. These methods include use of dowel connectors alone, bonding agent alone, combined use of dowel connectors and bonding agent and without using of dowel connectors and bonding agent, the use of micro-concrete is common for all the methods. All four methods are to be employed for jacketing of RC beams with the smooth surface as well as the chipped surface. Fig 1.6 shows details of RC beams to be strengthened by using various methods of jacketing.

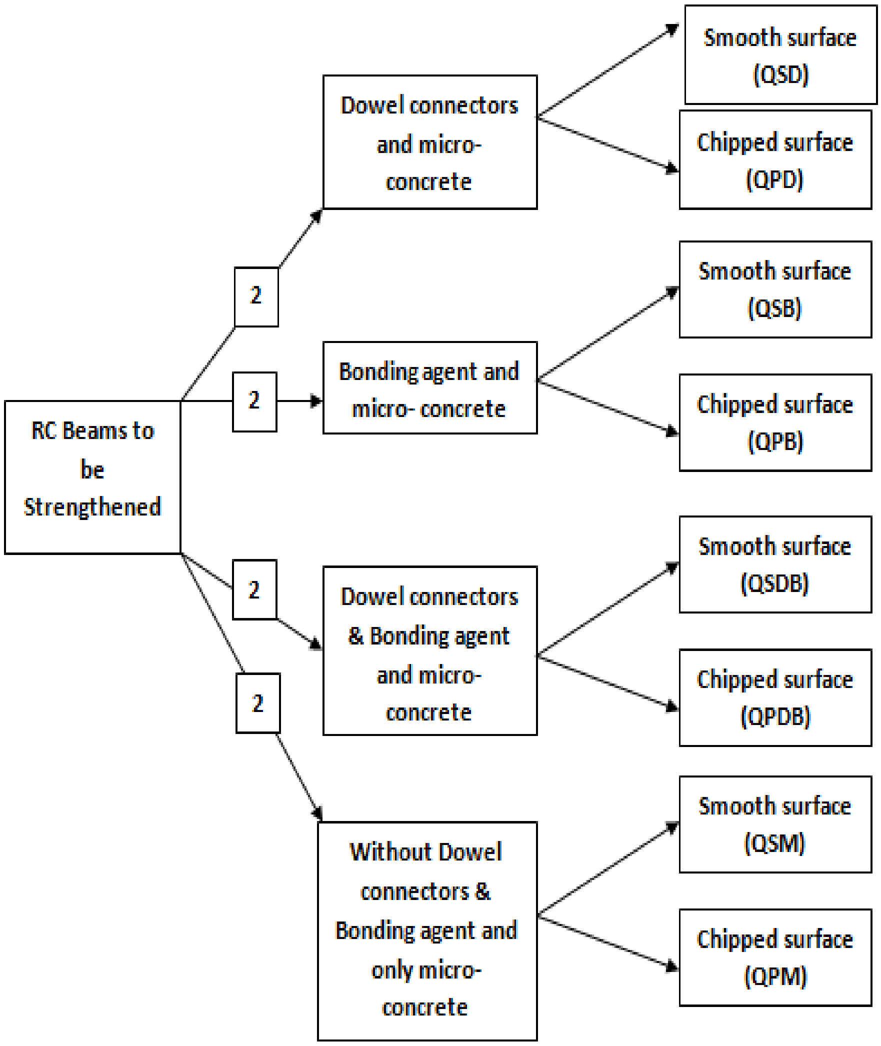



Figure 1.6: Details of RC beams to be Strengthened by various Jacketing methods

- Category - II consists of ten RC beams. Two beams res to be considered as control beams. Remaining eight beams are loaded up to their ultimate failure. After that these beams are repaired by grouting and then strengthened by jacketing. Out of these eight beams, surfaces of four beams are to be kept as cast and surfaces of remaining four beams are to be chipped up to 10mm to 15mm all around the beams. Four different methods are to be employed for jacketing of eight RC beams. Fig 1.7 shows details of RC beams to be repaired and strengthened by using various methods of jacketing

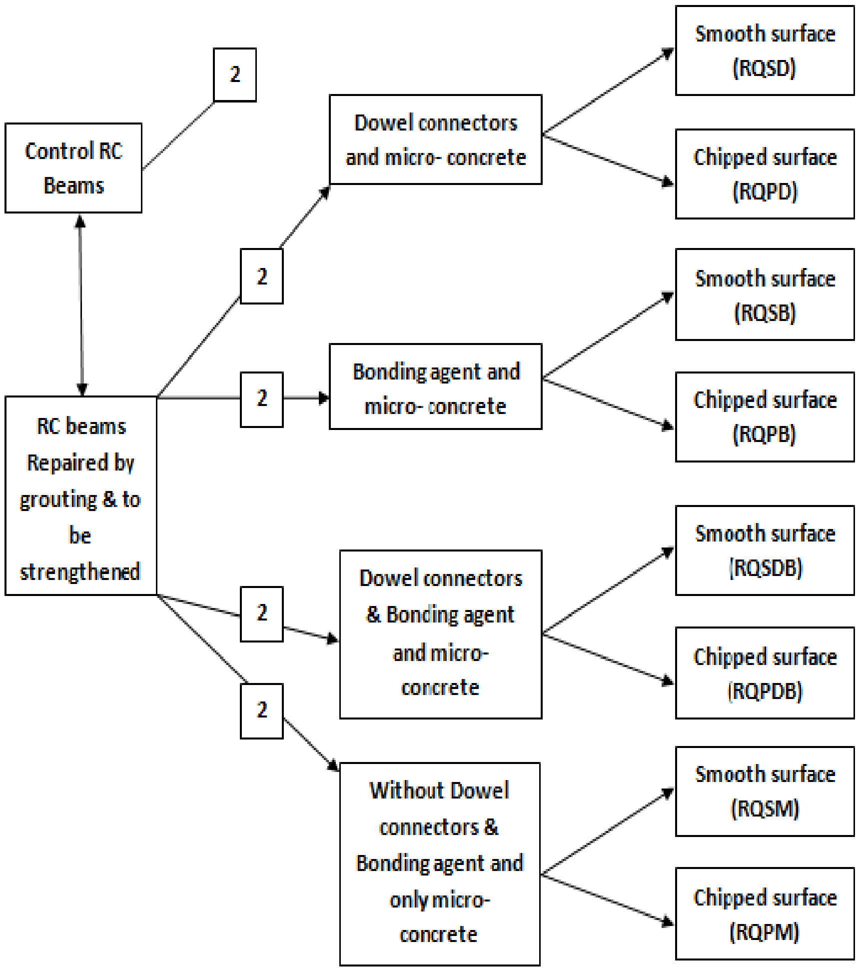



Figure 1.7: Details of RC Beams to be Repaired and Strengthened by various Jacketing Methods

- Grade of concrete to be use for casting of all RC beams is M-15.
- The design of RC beams are to be carried out using IS 456[4] provisions and uniform curing of 28 days is to be given to all the specimens. The jacketing is to be carried out for all beams after completion of curing.
- The RC beams are to be subjected to two point loading during the testing.
- Following parameters are to be evaluated for all the beams during the investigation.

  - Ultimate load carrying capacity
  - Deflection at mid span and at point load
  - Strain in concrete at various locations
  - Crack patterns
  - Failure mode

- Maximum load carrying capacity is to be computed analytically and to be compared with experimental results in case of all the beams.

## 1.6 Organization of the Report

The report may be viewed as divided into six chapters.

**Chapter 1**, includes introductory part, strengthening of RC beams, research significance, objectives of study and scope of work.

**Chapter 2**, discusses literature review. The details of work carried out by various researchers pertaining to jacketing of RC beam, column and bond strength between old to new concrete is presented in this chapter.

**Chapter 3**, consists of design of control RC beam and jacketed RC beam.

**Chapter 4**, includes the details of the experimental work conducted in major project. It also highlights in detail different types of material and techniques which are used for jacketing of RC beams, testing setup and details of instrumentation.

**Chapter 5**, includes test results of failure load, deflection and strain for strengthened beams. It also contains discussion of results in tabular form and graphical representation. Failure mode and crack pattern of tested RC beams also has been included. Analytical and experimental results for RC beams are compared

**Chapter 6** includes test results of failure load, deflection and strain for repaired and strengthened beams. It also contains discussion of results in tabular form and graphical representation. Failure mode and crack pattern of tested RC beams also has been included. Analytical and experimental results for RC beams are compared.

# Chapter 2

# Literature Survey

## 2.1 General

Strengthening of RC elements conducted by employing methods like steel plate jacketing, use of FRP composites and use of addition reinforcement,etc. RC elements are wrapped by carbon ?bre or glass fibre for strengthening. Information available in literature has been studied related to RC beams strengthened using additional reinforcement is presented in this chapter.

## 2.2 Jacketing of Reinforced Concrete Elements

**Fatih Altun** [**5**] studied flexural behaviour of RC beams. Jacketing was done by using additional reinforcement by using reinforced concrete. Nine RC beams were used during the experiment. Three different types of RC beams in each of the three size groups of 15 cm x 15 cm x 200 cm, 20 cm x 15cm x 200 cm, and 20 cm x 20 cm x 200cm dimensions were produced as under-reinforced and subjected to simple bending until full failure before jacketing. After application of loading the outer clearance part between the stirrups and the outer edge of these beams were trimmed off. When the outer parts of the 15cm x 15cm, 20cm x 15cm, 20cm x 20cm cross-sections were stripped off and remaining section were approximately 13cm x 13cm, 18cm x 13cm, 18cm x18cm prisms confined by the original stirrups.

Lateral and longitudinal reinforcement steel of the old and new beams were joined together by welding limbs of Z bars to corresponding bars of the old and new beams before concreting. The welded Z bars were 8 mm in diameter and placed 40 cm apart. Following Fig.2.1shows implementation of jacketing reinforcement and Z bars.

Figure 2.1: Jacketing Reinforcement around the Cores of initially Damaged RC beams using Welded Z Bars

Jacketing thickness was employed as 10 cm from all around. After jacketing dimensions of beams were 35cm x 35cm, 40cm x 35cm, 40cm x 40cm tested under two point load system. Fig.2.2 shows test setup for the beam. After jacketing it was noted that the mechanical behaviour of the jacketed RC beams are similar to and slightly better than those ordinary RC beams of the same dimensions, despite the fact that the core parts of the jacketed RC beams were fully damaged. Design of beam was conducted using british standards-8110.

The ultimate single load was taken,

$$P_u = \frac{3M_u}{Ł} \tag{2.1}$$


Figure 2.2: Test set up of jacketed RC beam

And ultimate resisting moment was taken,

$$M_u = \rho b d^2 f_{sc}(1 - 0.59\rho\frac{f_{sc}}{f_{cc}}) \tag{2.2}$$

Where,$P_u$ and $M_u$ are ultimate load and ultimate moment carrying, respectively. Experimental determination of load versus mid section displacements for the initial and jacketed RC beams are given in Fig.2.3 respectively.

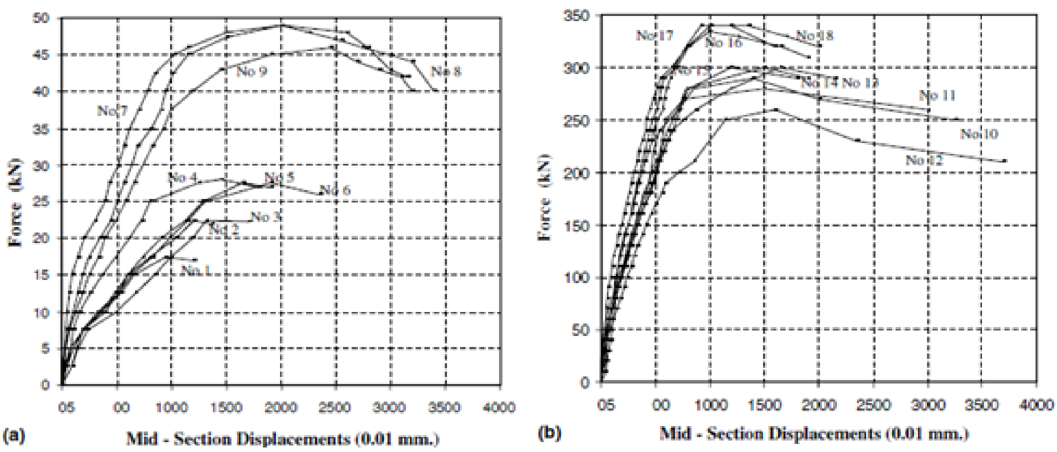



Figure 2.3: Experimental determination of load versus mid section displacements for Initial and Jacketed RC Beams

**Cheong and MacAlevey [6]** described an experimental investigation into the behaviour of reinforced concrete beams strengthened by jacketing. Static and dynamic load tests to failure were carried out on 61 slant shear prisms and 13 jacketed reinforced concrete T-beams. The concrete used in the jacket was preplaced aggregate concrete. The strength of the bond between preplaced aggregate concrete and plain concrete was assessed by slant shear tests. Initial beam size was 155mm x 175mm. Before jacketing the beam surfaces were made rough by electric chisel in two ways as "fully roughened" and "partially roughened" . Jacketing thickness on bottom and side of the beam was 100 mm and 55 mm, respectively. Little difference was observed in the behaviour of jacketed beams whose interfaces have been "fully roughened" or "partially roughened" , which exhibited the beneficial effect of roughening, when carried out with impact tools. Fig. 2.4 and 2.5 shows cross section details and test setup of jacketed beam. Fig. 2.6 shows load versus mid span displacement for jacketed T-beam.

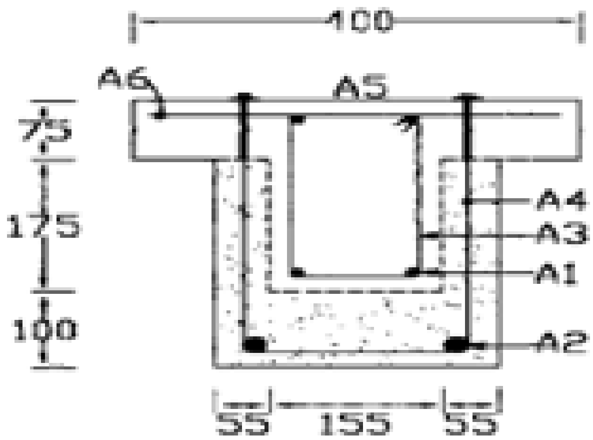



Figure 2.4: Cross section detail of jacketed beam

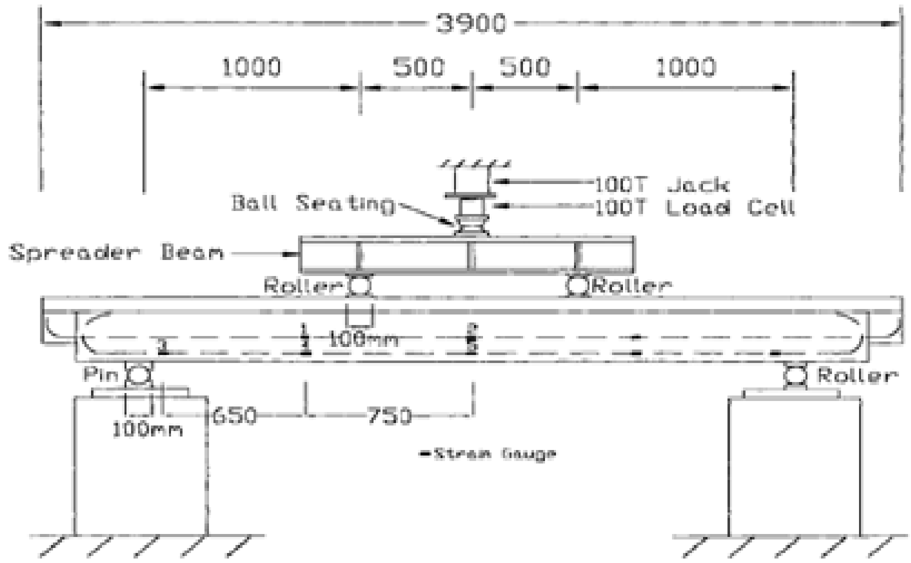



Figure 2.5: Test setup of jacketed beam

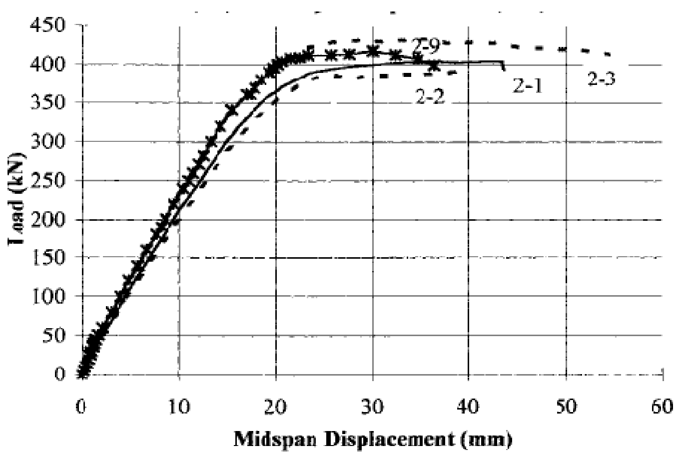



Figure 2.6: Load versus Mid Span Displacement for Jacketed T-beam

**Konstantinos et al.** [9] presented an experimental investigation of the effectiveness of strengthening reinforced concrete columns by placing concrete jackets. Three alternative methods of concrete jacketing are investigated and results are compared with results from an original unstrengthened specimen and a monolithic specimen. The unstrengthened column and the original columns of the strengthened specimens were designed to old 1950s Greek Codes. Poured concrete or shotcrete was used to construct the jackets of the strengthened specimens. Various other construction procedures were conducted in order to evaluate effectiveness of jacketing. These procedures were (a) welding the jacket stirrup ends together, (b) placing dowels and jacket stirrup end welding together and (c) placing bent down steel connector bars welded to the original column longitudinal reinforcement bars and the respective bars of the jacket. Fig. 2.7 ,2.8 and 2.9 show details of bent down steel connectors geometry, bent down bars as used in practice and welded jacket stirrup geometry, respectively.

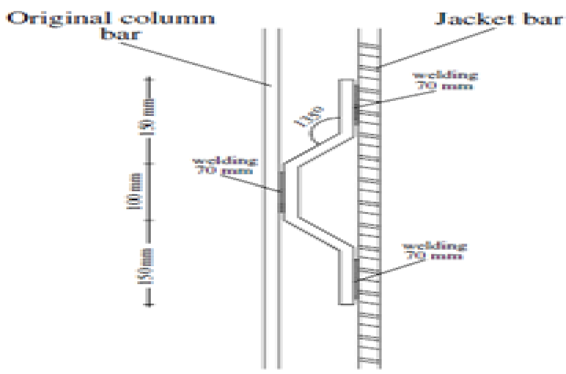



Figure 2.7: Bent down Steel Connectors Geometry

Figure 2.8: Bent down bars as used in Practice

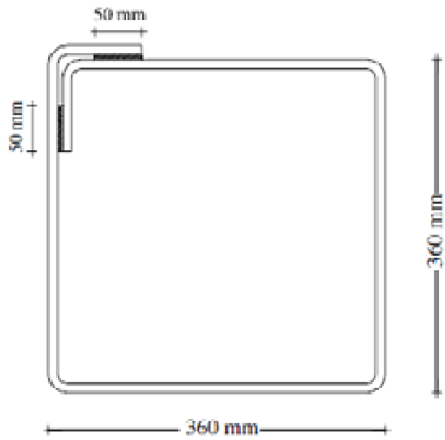



Figure 2.9: Welded Jacket Stirrup geometry

Initial column size was 250mm x 250mm and 75mm thickness of jacketing was done on all surfaces. Fig. 2.10shows geometrical characteristics of jacketed column. In order to investigate the lower limit of the effectiveness of the technique, the case of no treatment at the interface between the original column and the jacketing was examined. For earthquake simulation, displacement controlled cyclic loading was used for the testing. The seismic performance of the tested specimens is compared in terms of strength, stiffness. It was found that welding the stirrup ends together stops the stirrups from opening and in turn, the longitudinal bars of the jacket do not buckle, resulting in to better maximum load capacity.

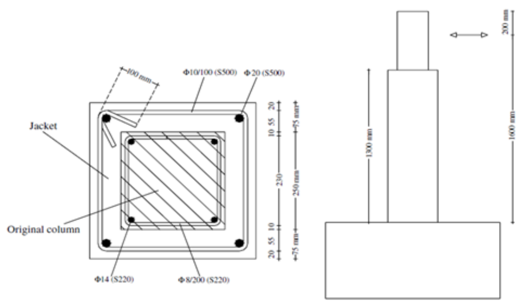



Figure 2.10: Geometrical Characteristics of Jacketed Column

**Ersoy et al.**[8] presented two series of tests made to study the behaviour of jacketed columns. The first series consisted of uniaxially loaded specimens and the behaviour of jacketed columns was compared with a monolithic specimen. The main objective of this series was to study the effectiveness of repair and strengthening jackets and the different between jackets made under load and after unloading. Original specimen was of 130mm x 130mm square dimensions and it was jacketed with 25 mm jacketing thickness all around. Specimens with repair and strengthening jackets behaved well when jacketing was introduced after unloading. Repaired jacketing made under load exhibited poor behaviour. Fig. 2.11 shows c/s dimensions of basic and jacketed column series-I.

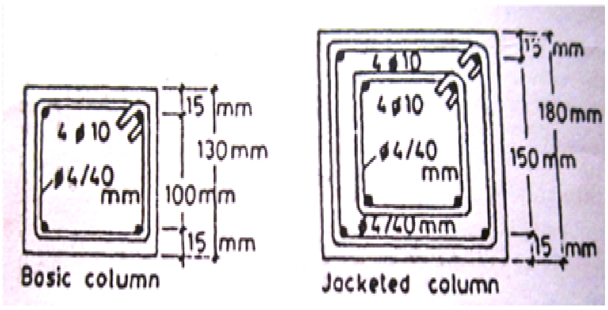



Figure 2.11: C/S Dimensions of Basic and Jacketed Column for series-I

In the second series, jacketed columns were tested under combined axial load and bending. Two monolithic specimens also were tested to serve as reference specimens. Original specimen was of 160mm x 160mm square dimensions and jacketed with 35 mm jacketing thickness all around. Before jacketing was introduced, the concrete cover was completely removed from the basic columns by chipping. So that the reinforcement was fully exposed. Longitudinal bars of the jacket were connected to those of the basic column by welded Z bars ties in the column consisted of two U-shaped bars that were lapped and welded. Effectiveness of repair and strengthening jackets was studied considering strength and stiffness. Fig. 2.12 shows c/s dimensions of basic and jacketed column and 2.13 shows reinforcement of jacketed columns of series II.

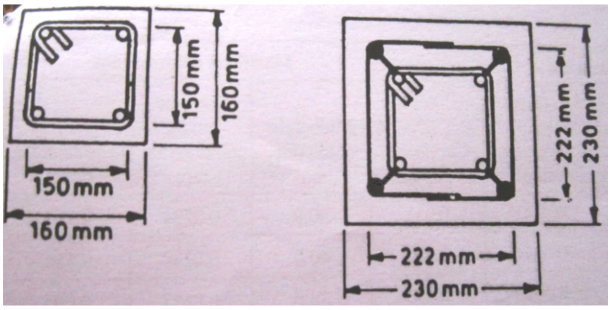



Figure 2.12: C/S Dimensions of Basic and Jacketed Column of series-II

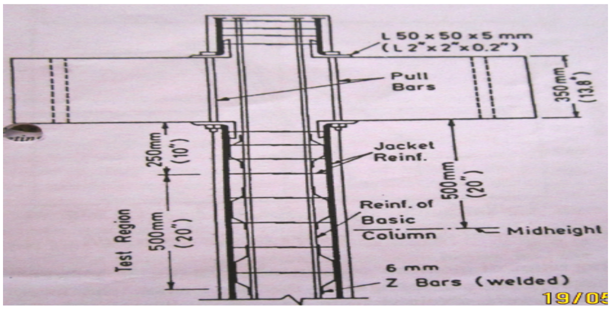
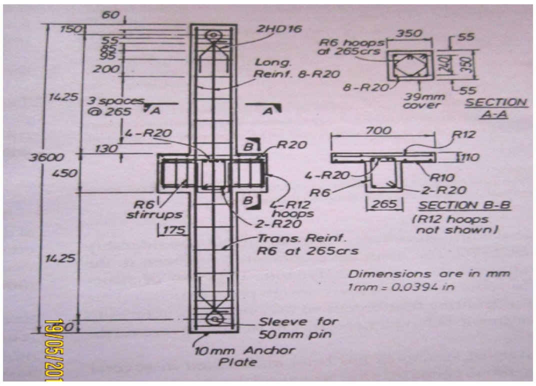



Figure 2.13: Reinforcement of Jacketed Column of Series II

**Rodriguez and Park [10]** examined four reinforced concrete columns were tested subjected to simulated seismic loading to investigate repair and strengthening techniques. The as built columns were 350mm square and contained low quantities of transverse reinforcement as was typical of building columns designed as construction prior to 1970. The column units represented the column region between the midheight of successive stories. A stub was present at midheight of each unit to represent a portion of the two way beams and slab at the beam column joint. Two columns units were tested, repaired and strengthened by jacketing and retested. The other two column units were strengthened by jacketing and tested. The jacketing consisted of a 100mm thickness of added reinforced concrete. The new longitudinal reinforcement was placed through the floor slab. The as-built columns displayed low available ductility and significant degradation of strength during testing, whereas jacketed column behaved in a ductile manner with higher strength and much reduced strength degradation. Fig.2.14 and 2.15 shows details of original and jacketed columns, respectively



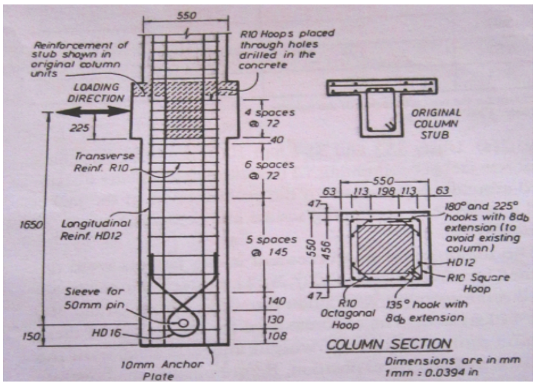




Figure 2.14: Details of Original Column

Figure 2.15: Details of Jacketed Column

**Julio et al.** [7] performed an experimental study to evaluate the bond between two concrete layers, using different techniques for investigating the roughness of the substrate and a commercial epoxy based bonding agent. For experiment total 40 slant shear half specimens and 40 pull-off half specimens first had the substrate surface prepared by wire brushing, sand blasting and chipping with jackhammer or were left as cast against steel formwork. Three month later, the bonding agent was applied and the new concrete was added. Fig. 2.16,2.17 and 2.18 show surface preparation by wire brushing, partial chipping and sand blasting, respectively. Fig. 2.19 shows application of bonding agent on substrate surface.

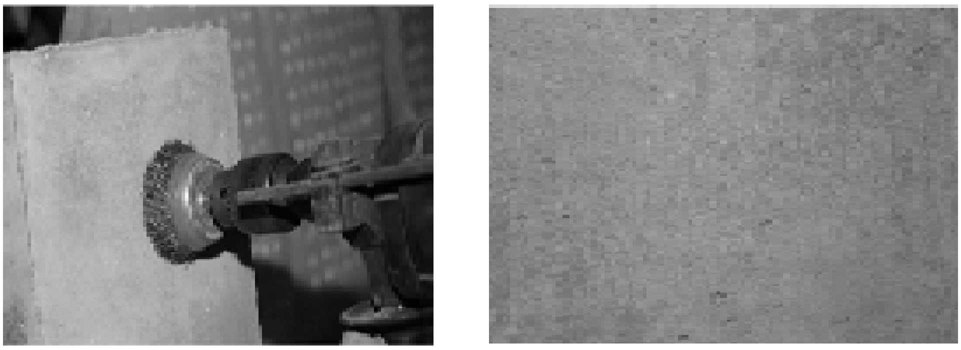


Figure 2.16: Wire Brushing

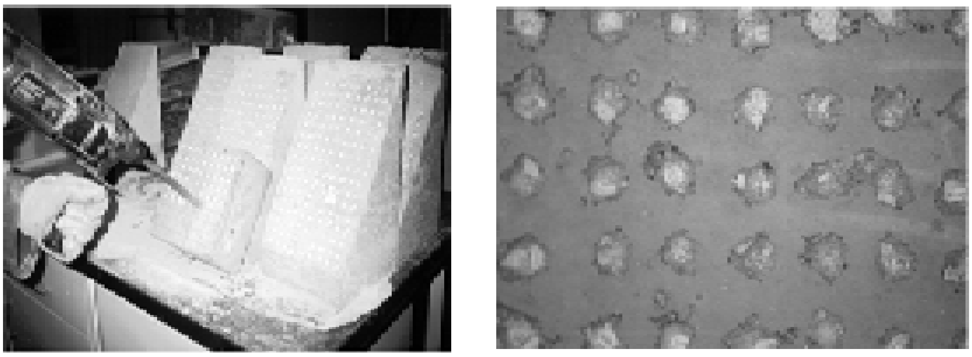


Figure 2.17: Partial Chipping

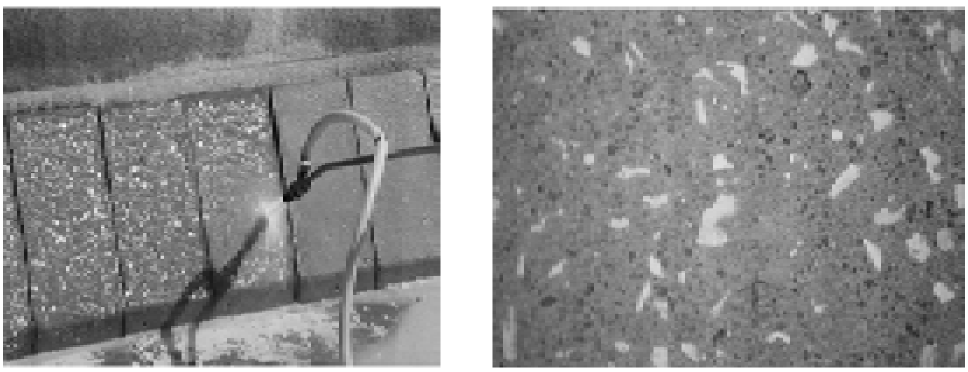


Figure 2.18: Sand Blasting

Figure 2.19: Application of bonding agent

Pull-off tests and slant shear tests were performed to evaluate the bond strength in tension and in shear. The adopted geometry for the slant shear specimens was 20 cm x 20 cm x 40 cm prism with the interface line at 300 to the vertical. The specimens were tested under compression using the standard procedure for the testing of cubes or cylinders for compressive strength. Fig. 2.20 shows slant shear test.

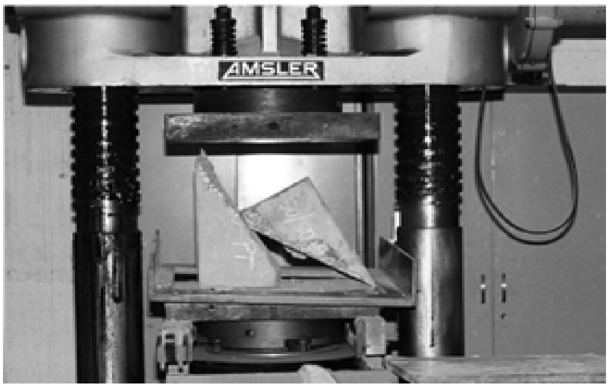



Figure 2.20: Slant Shear Test

The adopted geometry for the pull-off specimens was a 20 cm cube with the interface line at the middle. A core of 75 mm diameter was drilled into the added concrete and extending 15 mm beyond the interface into the substrate. A circular steel disc was bonded with an epoxy resin to the surface of the core. A tension force was applied to the disc with a commercial device at a steady rate of 0.05 MPa until failure occurred. Fig. 2.21 shows pull-off test.

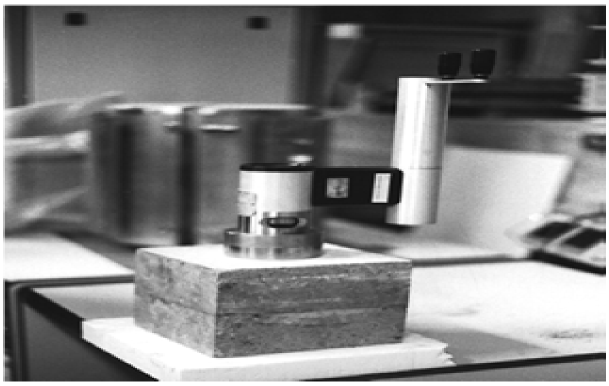


Figure 2.21: Pull-Off Test

Analysis of the results indicated that the application of an epoxy-based bonding agent does not improve the bond strength since the adopted method for surface preparation adequately increased its roughness. Partial chipped surface coated with bonding agent showed superior results compared to other combinations.

# Chapter 3

# Design of RC Beams

## 3.1 General

The RC beams cast for experimental works are designed based on IS provisions. Sample calculations for jacketed beam design are also covered in this chapter.

## 3.2 Control RC Beams

Design of control beam has been conducted based on provisions of IS-456[8]. Beams are designed as under-reinforced section. The grade of concrete for the beam is assumed as M15. It is further assumed that the beam is required to be strengthened by jacketing as it had been designed using codal provisions before 30 years. The details of RC beams are given as follows:

N.A of RC beams

$$X_{umax} = 0.48xd \tag{3.1}$$

| | | |
|---|---|---|
| Span of beam (L) | = | 2100 mm |
| Width (b) | = | 150 mm |
| Overall depth (D) | = | 300 mm |
| Clear cover | = | 25 mm |
| Effective depth (d) | = | 275 mm |
| Grade of Concrete ($f_{ck}$) | = | M15 |
| Grade of Steel ($f_y$) | = | 415 MPa |

$X_{umax}$ =132 mm

$$M_u = (0.36 \times \frac{X_{umax}}{d})[1 - 0.42 \times \frac{X_{umax}}{d}] \times b \times d^2 \times f_{ck} \tag{3.2}$$

$M_u$ =23.48 kN.m

$$Minimum A_{st} = \frac{(0.87 \times b \times d)}{f_y} \tag{3.3}$$

Minimum $A_{st}$ =84.49 $mm^2$

$$Maximum A_{st} = (0.04 \times b \times D) \tag{3.4}$$

Maximum $A_{st}$ = 1800 $mm^2$

$A_{stprov}$ = 100.48 $mm^2$ > 84.49 $mm^2$ (Ok)

Provide 2 nos-8 mm diameter bars as tension reinforcement.

Now actual neutral axis,

$$\frac{X_u}{d} = \frac{0.87 \times f_y \times A_{stprov}}{0.36 \times f_{ck} \times b \times d} \tag{3.5}$$

$\frac{X_u}{d}$ = 0.1629

Substituting above value in equation 3.2.

$M_u$ =9.29 kN.m

Now, distance between supports and point load is denoted by "a" shown in Fig. 3.1

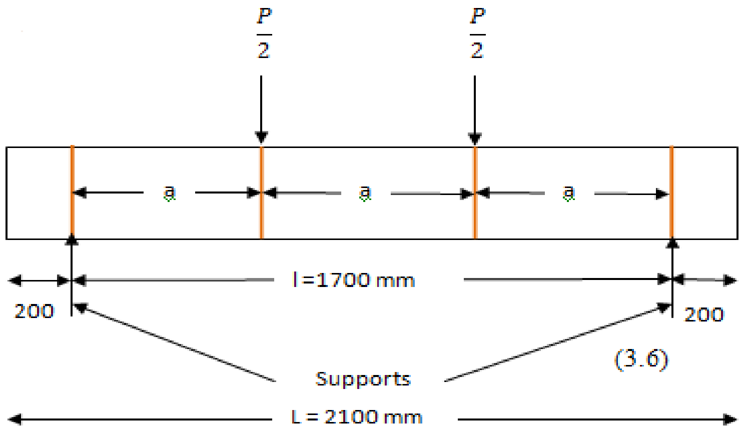



Figure 3.1: Distance Between Supports and Point Load

a= $\frac{L-400}{3} = 567$ mm $= 0.567$ m

Now, $\frac{P}{2} = \frac{M_u}{a}$

P $= 32.80$ kN.

**Shear Reinforcement**

$V_u = \frac{P}{2} = 16.40$ kN

$$\tau_v = \frac{V_u}{b \times d} \tag{3.6}$$

$\tau_v = 0.3977$ N$/mm^2$

$\tau_c = 0.35$ N$/mm^2$ from IS-456[8]

$\tau_c < \tau_v$

So, Shear reinforcement is required.

$$V_{us} = V_u - b \times d \tag{3.7}$$

$V_{us}$ = 2.63 kN

Adopt 2 legged 6 mm diameter stirrups.

$$S_v = (\frac{0.87 \times f_y \times A_{sv} \times d}{V_{us}}) \tag{3.8}$$

$A_{sv}$ = Area of 6 mm diameter stirrups = 56.52 $mm^2$

$S_v$ = 1286.83 mm

$$S_v = (\frac{0.87 \times f_y \times A_{sv}}{0.4 \times b}) \tag{3.9}$$

$S_v$ = 340.11 mm

$$S_v = 0.75 \times d \tag{3.10}$$

$S_v$ = 206.25 mm

And, $S_v$ = 300 mm

So, provide 6 mm diameter 2- legged vertical stirrups @ 200 mm c/c.

Fig.3.2 shows reinforcement details for control RC beam.

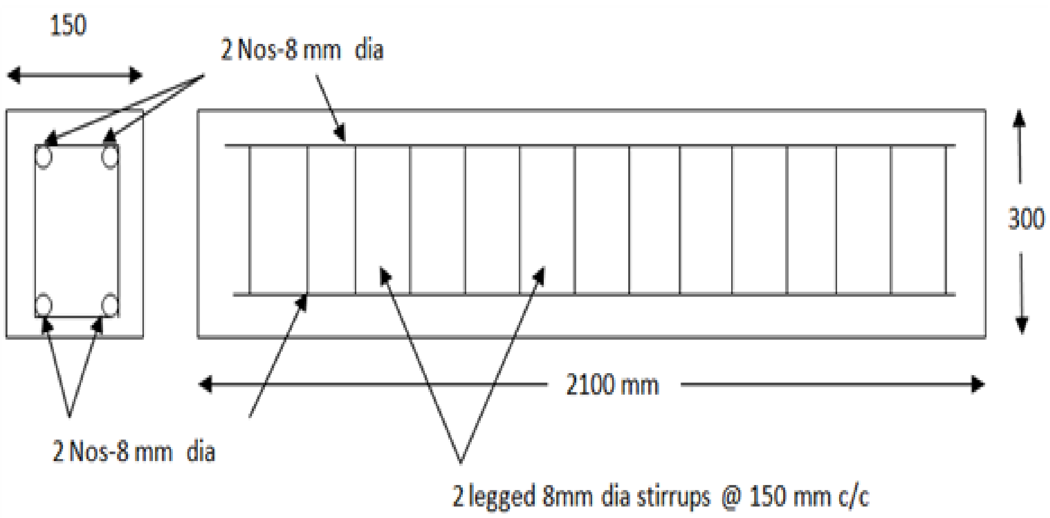



Figure 3.2: Reinforcement Details of Control Beam

## 3.3 Jacketed RC Beams

After 28 days of curing period, the RC beams are jacketed. The dimensions of beam the jacketed beam is considered as 270 mm x 420 mm x 2100 mm. Thickness of jacketing is considered based on assumption of 20 mm clear cover and 6 mm diameter stirrups are to be provided. For making new concrete easily flowable through section of jacketing, projection from inner beam surface to the face of new reinforcement stirrups is assumed as 37 mm. Therefore, total jacketing thickness is kept 60 mm all around. Beams are designed as under-reinforced section.

Fig 3.3 shows cross-section of jacketed beam.

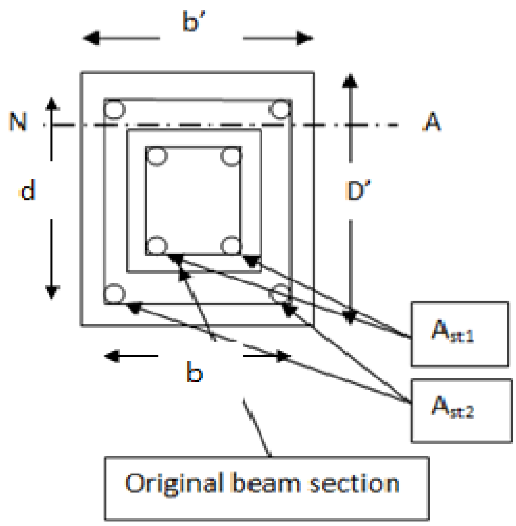



Figure 3.3: Cross-Section of Jacketed beam

Fig3.4 shows Stress Diagram for Jacketed section.

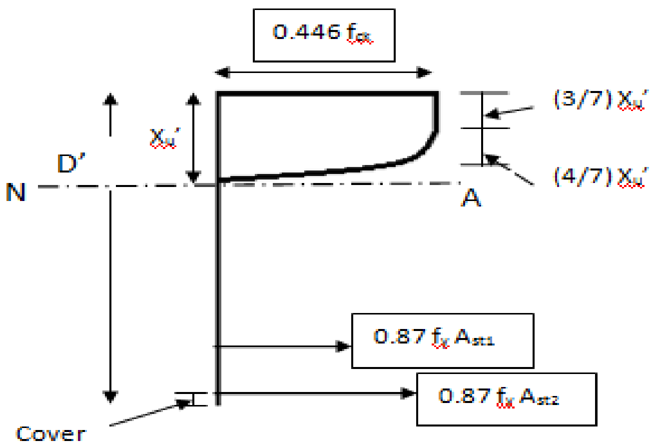



Figure 3.4: Stress Diagram for Jacketed section

| | | | | |
|---|---|---|---|---|
| Span of beam (L') | | | = | 2100 mm |
| Width (b') | = | b + 60 + 60 | = | 270 mm |
| Overall depth (D') | = | d + 60 + 60 | = | 420 mm |
| Clear cover | | | = | 20 mm |
| Effective depth (d') | | | = | 400 mm |
| Grade of Concrete ($f'_{ck}$) | | | = | M58.16 |
| Grade of Steel ($f'_y$) | | | = | 415 MPa |
| Area of tension reinforcement control beam ($A_{st1}$) | | | = | 100.48 $mm^2$ |

Design of jacketed beam QSD is given below,

N.A of RC beams

$$X_{umax} = 0.48 \times d' \tag{3.11}$$

$X_{umax}$ =192 mm

$$M_u = (0.36 \times \frac{X_{umax}}{d'})[1 - 0.42 \times \frac{X_{umax}}{d'}] \times b' \times d'^2 \times f'_{ck} \tag{3.12}$$

$M_u$ =89.40 kN.m

$$Minimum A_{st} = \frac{(0.87 \times b' \times d')}{f_y} \tag{3.13}$$

Minimum $A_{st}$ =221.21 $mm^2$

$$Maximum A_{st} = (0.04 \times b' \times D') \tag{3.14}$$

Maximum $A_{st}$ = 4536 $mm^2$

$A_{stprov}$ = 226.08 $mm^2$ > 221.21 $mm^2$ (Ok)

Provide 2 nos-12 mm diameter bars as tension reinforcement.

Assuming actual neutral axis to be lying in jacketed section on compression side,

$$[0.446\times f'_{ck}\times b'\times(\frac{3}{7})\times X'_u]+(\frac{2}{3})\times[0.446\times f'_{ck}\times b'\times(\frac{3}{7})\times X'_u] = (0.87\times f_y\times A_{st1})\times(0.87\times f_y\times A_{st2}) \tag{3.15}$$

Where, $0.446 f'_{ck}$ = Permissible bending compressive stress in concrete.

0.87 x $f_y$ x $A_{st1}$ = Permissible stress in tension steel in control beam.

0.87 x $f_y$ x $A_{st2}$ = Permissible stress in tension steel in jacketed beam.

$X_u$ = 20.80 mm from top surface shown in fig. 3.4

Thus, neutral axis of jacketed beam is within 60 mm of jacketing portion.

Substitute value of $X_u$ instead of $X_{umax}$ in equation 3.12

$M_u$ = 46 kN.m

Moment due to Self weigth of beam

Self weigth of beam $W_1$ = 0.27 x 0.42 x 24 = 2.72 kN/m

l = distance between two supports = 2100-400 =1700 mm

Now, distance between supports and point load is denoted by "a" as shown in fig. 3.1

a= $\frac{L-400}{3}$ = 567 mm = 0.567 m

$$M_1 = (\frac{W_1\times l\times a}{2}) - (\frac{W_1\times a\times a}{2}) \tag{3.16}$$

$M_1$ = 0.87 kN.m

Moment due to self weight of I- section, roller and plates.

Assuming weight of I-section, roller and plates as 0.3 kN, 0.04 kN and 0.08 kN, respectively.

$$W_2 = (\frac{Wt.of I - Section}{2}) + (\frac{Wt.of Rollar}{2}) + (\frac{Wt.of Plates}{2}) \tag{3.17}$$

$W_2$ = $(\frac{0.3}{2})$ +$(\frac{0.04}{2})$ + $(\frac{0.08}{2})$

$W_2$ = 0.21 kN

$$M_2 = W_2 \times a = 0.12kN.m \tag{3.18}$$

$$TotalmomentM = M_u + M_1 + M_2 \tag{3.19}$$

M = 46.99 kN.m

Now, $\frac{P}{2} = \frac{M}{a}$ P = 165.87 kN.

**Shear Reinforcement**

$V_u = \frac{P}{2}$ = 82.94 kN

$$\tau_v = \frac{V_u}{b' \times d'} \tag{3.20}$$

$\tau_v$ = 0.7680 N/$mm^2$

$\tau_c$ = 0.334 N/$mm^2$from IS-456[8]

$\tau_{cmax}$ = 4 N/$mm^2$ $> \tau_v$ from IS-456[8]

$\tau_c < \tau_v$

So, Shear reinforcement is required.

$$V_{us} = V_u - b' \times d' \tag{3.21}$$

$V_{us}$ = 46.86 kN

Adopt 2 legged 6 mm diameter stirrups.

$$S_v = \frac{0.87 \times f_y \times A_{sv} \times d'}{V_{us}} \tag{3.22}$$

Where $A_{sv}$ = Area of 6 mm diameter stirrups = 56.52 $mm^2$

$S_v$ = 164.92 mm

$$S_v = \frac{0.87 \times f_y \times A_{sv}}{0.4 \times b'} \tag{3.23}$$

$S_v$ = 188.95 mm

$$S_v = 0.75 \times d' \tag{3.24}$$

$S_v$ = 300 mm

And $S_v$ =300 mm

So, provide 6 mm diameter 2- legged vertical stirrups @ 150 mm c/c.

Fig.3.5 shows reinforcement details for jacketed RC beam.

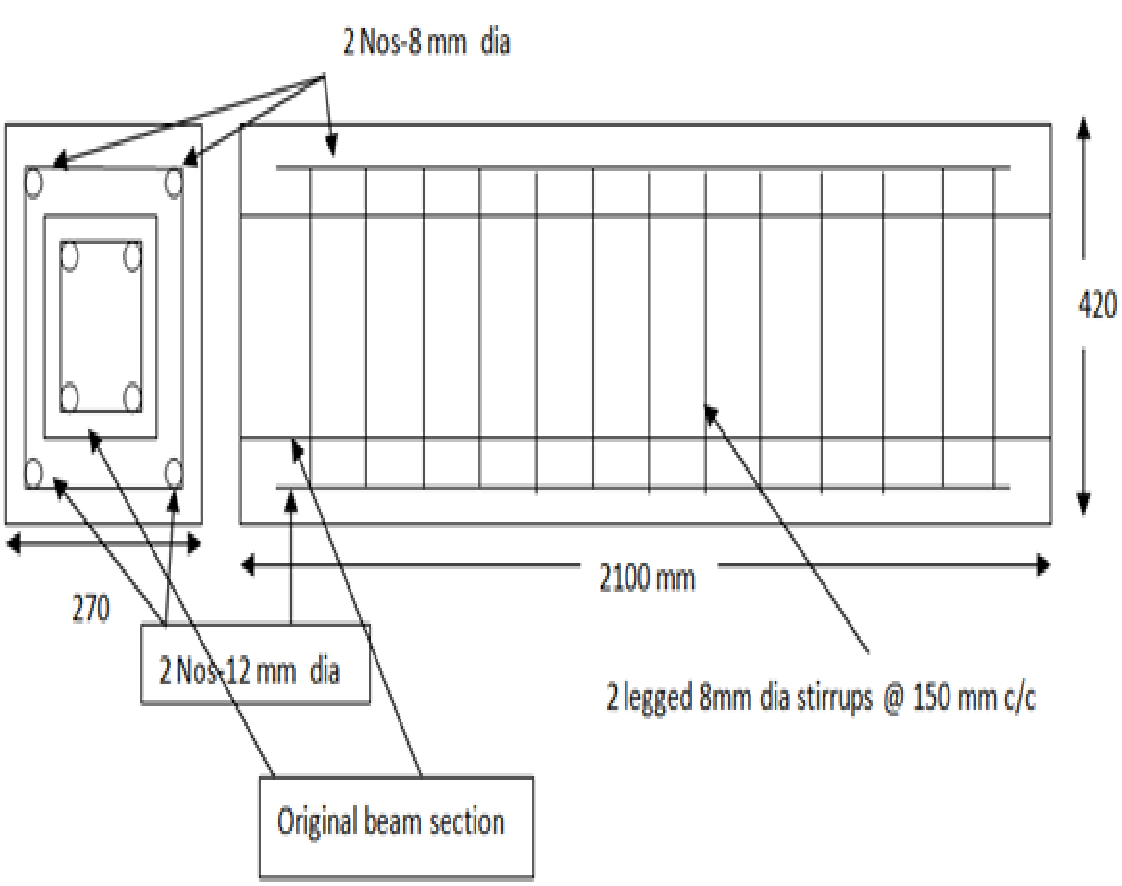



Figure 3.5: Reinforcement Detail for Jacketed Beam QSD

For all other strengthened beams by using similar process as explained above the analytical failure load has been computed and reported as given in Table 3.1.

Table 3.1: Analytical Failure Load for Strengthened Beams

| Sr. No | Specimens Notations | Analytical Failure Load(kN) |
|---|---|---|
| 1 | QSD | 165.87 |
| 2 | QSB | 166.41 |
| 3 | QSDB | 165.85 |
| 4 | QSM | 165.67 |
| 5 | QPD | 165.22 |
| 6 | QPB | 165.22 |
| 7 | QPDB | 165.42 |
| 8 | QPM | 165.92 |

Table 3.2: Analytical Failure Load for Repaired and Strengthened Beams

| Sr. No | Specimens Notations | Analytical Failure Load(kN) |
|---|---|---|
| 1 | C1 | 32.81 |
| 2 | C2 | 32.81 |
| 3 | RQSD | 165.04 |
| 4 | RQSB | 165.55 |
| 5 | RQSDB | 165.25 |
| 6 | RQSM | 165.44 |
| 7 | RQPD | 165.16 |
| 8 | RQPB | 165.22 |
| 9 | RQPDB | 165.16 |
| 10 | RQPM | 164.91 |

Table 3.2 shows analytical load computed for repaired and Strengthened beams using the procedure explained in this section.

# Chapter 4

# Experimental Work

## 4.1 General

Casting of RC beams and process of strengthening of RC beams is covered in this chapter. Details about procedure, preparations and methodology for strengthening beams are covered. Details of flexure tests on beams including instruments used are further included.

## 4.2 Casting of Beams

Castings of all 18 beams are conducted by using M15 concrete grade mix. Mix design of M15 concrete has been made. Concrete mix proportion selected is shown in Table 4.1

Table 4.1: Concrete mix proportion

| Grade of concrete | Water | Cement | Sand | Coarse Aggregate |
|---|---|---|---|---|
| M15 | 0.6 | 1 | 3.25 | 5 |

**Proportions of ingredients used for $1m^3$ concrete mix are given as follows:**

| | | |
|---|---|---|
| Cement | = | 270 kg/m3 |
| Sand | = | 877.5 kg/m3 |
| 10 mm aggregate | = | 945 kg/m3 |
| 20 mm aggregate | = | 405 kg/m3 |
| Free water | = | 162 kg/m3 |
| w/c | = | 0.6 |

Table 4.2 shows average cube strength of 3cubes after 28 day of curing which has been taken at the time of casting of beams.

Table 4.2: Average Cube Strength

| Sr. No | Specimens Notations | Cube Strength(Mpa) | Avg. Cube Strength (Mpa) |
|---|---|---|---|
| 1 | C1 | 21.55, 24 | 22.77 |
| 2 | C2 | 21.55, 24 | 22.77 |
| 3 | QSD | 20.89 | 20.89 |
| 4 | QSB | 18.67, 16.44, 16.67 | 17.26 |
| 5 | QSDB | 21.11, 23.11 | 22.11 |
| 6 | QSM | 20.89 | 20.89 |
| 7 | QPD | 18.67, 16.44, 16.67 | 17.26 |
| 8 | QPB | 21.78, 23.33 | 22.56 |
| 9 | QPDB | 21.11, 23.11 | 22.11 |
| 10 | QPM | 18.22 | 18.22 |
| 11 | RQSD | 16.44, 18.65 | 17.55 |
| 12 | RQSB | 19.56, 18 | 18.78 |
| 13 | RQSDB | 24.22, 24.86, 25.33, 24 | 24.66 |
| 14 | RQSM | 24.66, 25.11 | 24.88 |
| 15 | RQPD | 16.44, 18.65 | 17.55 |
| 16 | RQPB | 24.22, 24.86, 25.33, 24 | 24.66 |
| 17 | RQPDB | 20.66 | 20.66 |
| 18 | RQPM | 20.66 | 20.66 |
| | | Average Value(N/mm2) | 20.90 |

The average value of cube compressive strength of concrete is 20.92 N/mm2. Reinforcement cage for control beam and jacketed beam is shown in Fig. 4.1 (a) and 4.1 (b), respectively.

Fig. 4.1(a) Reinforcement cage for Control beam

Fig. 4.1(b) Reinforcement cage for jacketed beam

Figure 4.1: Reinforcement Detail for Control Beam and Jacketed Beam

Fig. 4.2 (a) shows placement of cage in form work for control beam and Fig. 4.2(b) shows curing of beams.

Fig. 4.2(a) Placement of cage in form work for Control Beam

Fig. 4.2(b) Curing of beams in Progress

Figure 4.2: Placement of cage in form work for Control Beam and Curing of beams in Progress

## 4.3 Material Properties

### 4.3.1 Micro-concrete [1]

MASTERFLOW 915 which is a product of BASF chemical company has been used as micro-concrete for jacketing of all 18 RC beams. MASTERFLOW 915 is Portland-cement-based, shrinkage-compensated, construction grout. Its non-metallic formula does not rust, bleed, or harm metals on contact.

Advantages of micro-concrete as under :

- Optimum contact with load bearing areas
- Pre packed and pre formulated
- Consistent performance
- Chloride free
- One component - mixes easily with water
- Dimensionally stable
- Dry pack to pourable consistency
- Coarse aggregates can be used for large volume

Micro-concrete is available in 25 kg bag. Typical Properties of micro-concrete is given in Table 4.3

Table 4.3: Typical Properties of micro-concrete

| Aspect | Free flow grew powder |
|---|---|
| W/P ratio by weight | 0.17 (Flowable) |
| Mix Density(Flowable) | 2100 kg/m$^3$ |
| Compressive Strength ( 70 mm cube) | 15 MPa at 1 day |
| | 25 MPa at 3 day |
| | 35 MPa at 7 day |
| | 50 MPa at 28 day |

Fig. 4.3 shows a micro-concrete bag.


Figure 4.3: Micro-concrete bag

### 4.3.2 Bonding Agent [2]

SALBOND-RX50 which is product Industrial Corporation of India is a two components epoxy system (Base and Curing Agent) which gives thick non porous and highly resistant films with excellent adhesion was used as bonding agent for beam jacketing. It is used for following purposes,

- Corrosion resistant coatings on metal surfaces as well as on concrete surfaces.
- For bonding between old and new concrete.
- Crack sealing.
- Foundation grouting.
- Industrial heavy duty floor toppings.
- For water proofing (sandwich layer as well as on open surfaces)

Typical properties of bonding agent are shown in Table 4.4

Table 4.4: Typical properties of Bonding Agent

| System | Two Components |
|---|---|
| Mixing Ratio | 2:1 Base and Curing Agent |
| Coverage | 4 to 6 Sq.mt./kg |
| Pot Life | 30 to 35 minutes |
| Application | By Brush, injection |
| Cleaning | Thinner |
| Storage and Selflife | 12 to 18 months in tight container |

Fig 4.4 (a) Shows containers of bonding agent and Fig 4.4 (b) Base and Curing agent, respectively

Fig. 4.4 (a) Containers of Bonding Agent

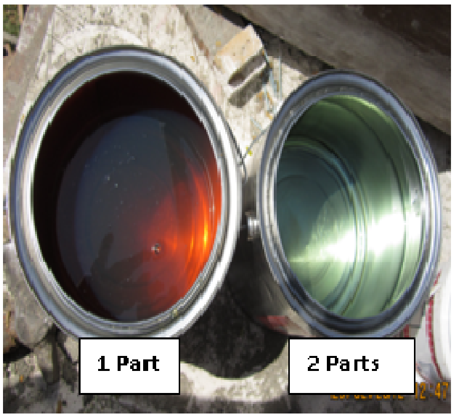



Fig 4.4 (b) Base and Curing agent

Figure 4.4: Containers of Bonding Agent and Base and Curing agent

### 4.3.3 Dowel Connectors

8mm diameter HYSD bars are used as dowel connectors. Dimensions of dowel connectors are chosen as of 120mm x 50 mm are used. Dowel connectors are fixed in concrete using the bonding chemical. Fig. 4.5 (a) and Fig. 4.5 (b) show dimensions of dowel connectors and bonding chemical, respectively.

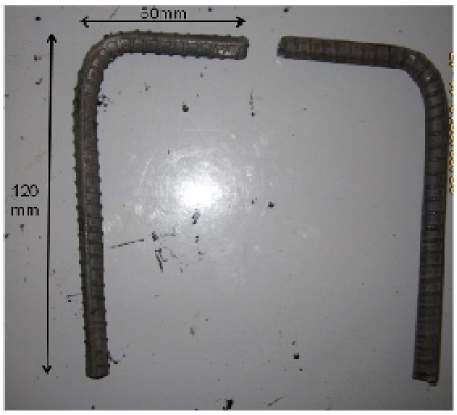



Fig. 4.5 (a) Dowel Connectors

Fig. 4.5 (b) Bonding Chemical for Dowel Connector

Figure 4.5: Dowel Connectors and Bonding Chemical for Dowel Connector

## 4.4 Procedure for Strengthening of Beams by Various Jacketing Method

Strengthening of RC beams is done by placing additional reinforcement around the beams. Strengthening is done on smooth and chipped surface for the beams. Smooth surface is obtained by keeping surface of the beam in as cast position in the formwork. Chipped surface is obtained by chipping outer part of the beam from all sides by 15 mm using electrical hammer. For removal of loose concrete on surface of beam water force is applied on the chipped beams. Fig. 4.6 (a) and Fig. 4.6 (b) show chipping process for beam and view of the beams after chipping. Before jacketing, surface of the beam is to be made free from contaminants such as oil, grease, curing membrane, dust, fungus, mass, etc.

Fig. 4.6 (a) Chipping Process for Beam

Fig. 4.6 (b) View of Beam after Chipping

Figure 4.6: Chipping Process for Beam and View of Beam after Chipping

Eight RC beams have been jacketed by 60mm thickness all-round. Adding 60 mm thickness of micro-concrete on both side faces of 150 mm width, width of beam due to jacketing become 270 mm after jacketing. Also adding 60 mm thickness of micro-concrete on both compression and tension sides to 300 mm depth beam, jacketed depth of the beam becomes 420 mm. Final cross-section of jacketed beam, thus has become 270mm x 420mm. Four methods have been employed for jacketing of RC beams in the present investigation. These methods include use of dowel connectors and micro-concrete, bonding agent and micro-concrete, combined use of dowel connectors, bonding agent and micro-concrete and without dowel connectors, bonding agent and only micro-concrete. All four methods have been employed for jacketing of RC beams with the smooth surface as well as the chipped surface, respectively.

- **Use of Dowel Connectors and Micro-concrete**

Dimension of dowel connectors is 120mm x 50mm. These connectors are fixed in the surface of beam up to 80mm as 10 times the diameter. Therefore outof 120mm length, 80mm length of connectors is inside of the concrete and the remaining 40mm length is extended up to new jacketing stirrups. Dowel connectors are to be fixed on 150 mm width side and 300 mm depth side surfaces of beam throughout the span of 2100 mm. On 300mm depth side, the dowel connectors are fixed on alternate stirrups at 300mm c/c distance in staggered pattern. On 150 mm side of the beam, the dowel connectors are fixed at centre of beam at 300mm c/c distance. Fig. 4.7 shows location of dowel connectors on the beam.

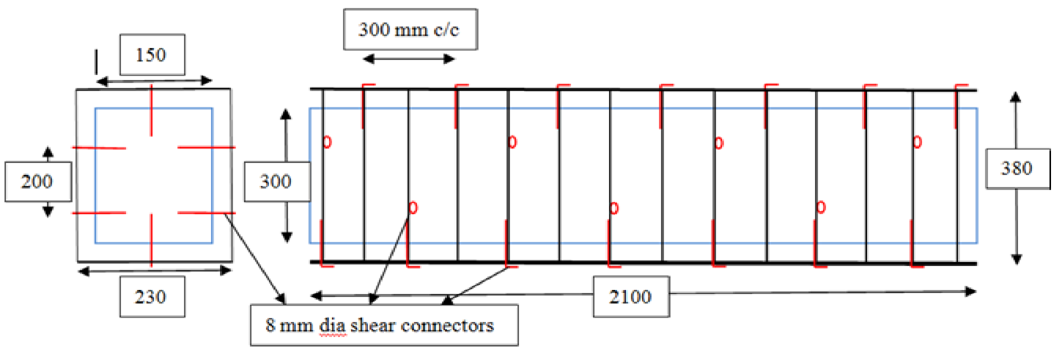



Figure 4.7: Location of dowel connectors on beam

For using dowel connectors the drilling is to be carried out along beam surface shown in Fig. 4.8 Accumulated rust in drilled holes is removed before fixing the dowel connectors inside concrete surface of the beam. Dowel connectors are fixed inside the concrete surface using bonding chemical. For preparation of bonding chemical for dowel connectors one part of curing agent and two parts of base is taken and mixed properly. Material properties for dowel connectors and bonding chemical is given in section 4.3.3. Fig 4.8 (a) and Fig 4.8 (b) show drilling process and application of dowel connectors, respectively.

Fig. 4.8(a) Drilling Process Dowel Connectors

Fig. 4. 8(b) Application of Dowel Connectors

Figure 4.8: Drilling Process Dowel Connectors and Application of Dowel Connectors

Jacketing is to be carried out by using micro-concrete. Properties of micro-concrete are discussed in section 4.3.1. For using micro-concrete, 17% of water by its weight and 40% grit of 6mm size is added and mixed using hand mixer. Fig. 4.9 (a) and Fig. 4.9 (b) show hand mixer for mixing the micro-concrete and view of the micro-concrete, respectively.

Fig. 4.9(a) Hand Mixer for Mixing Micro-Concrete

Fig. 4.9 (b) view of micro-concrete

Figure 4.9: Hand Mixer for Mixing Micro-Concrete and view of micro-concrete

Waterproof Wooden formwork has been used for the jacketing process. Fig 4.10 shows view of the wooden formwork. The dowel connectors are applied on both smooth surface and chipped surface of the beam and is shown in Fig. 4.11 (a) and Fig. 4.11 (b) respectively.

Figure 4.10: Wooden Formwork for Jacketing


Fig. 4.11(a) Application of Dowel connectors for Beam with Smooth Surface

Fig. 4.11(b) Application of Dowel connectors for Beam with Chipped Surface

Figure 4.11: Application of Dowel connectors for Beam with Smooth Surface and Application of Dowel connectors for Beam with Chipped Surfac

- **Use of Bonding Agent and Micro-concrete**

Detail of bonding agent is given in section 4.3.2. For mixing bonding agent two parts of base and one part curing agent is taken in a bowl. Both materials are mixed and the mix is applied by brush on the beam surface. Fig. 4.12 (a) and Fig. 4.12 (b) show mixing and application of bonding agent on the beam, respectively.

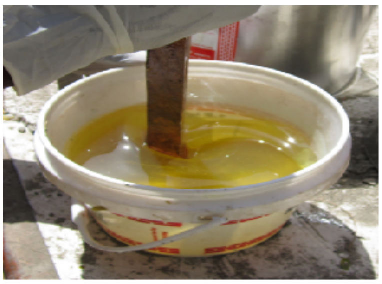


Fig. 4.12(a) Mixing of Bonding Agent

Fig. 4.12(b) Application of Bonding Agent on Beam

Figure 4.12: Mixing of Bonding Agent and Application of Bonding Agent on Beam

After application of bonding agent on the beam, micro-concrete is used for jacketing. The casting of beam using micro-concrete is carried out within 30 to 35 minutes. The bonding agent is applied on smooth surface beam and chipped surface beam is shown in Fig. 4.13 (a) and Fig. 4.13 (b), respectively.

Fig. 4.13(a) Application of Bonding Agent for Beam with Smooth Surface


Fig. 4.13(b) Application of Bonding Agent for Beam with Chipped Surface

Figure 4.13: Application of Bonding Agent for Beam with Smooth Surface and Application of Bonding Agent for Beam with Chipped Surface

- **Use of Dowel Connectors and Bonding Agent with Micro-concrete**

This strengthening method incorporate combined use of dowel connectors and bonding agent with micro-concrete for beams. Details of application of bonding agent and location of dowel connector have already covered in above sections. First dowel connectors are fixed on the concrete surface of beam. After that the bonding agent is applied on the beam surface. After application of the bonding agent casting of jacketed beam using micro-concrete is completed within 30 to 35 minutes. Use of dowel connectors and bonding agent is applied on smooth surface and chipped surface beam is shown in Fig. 4.14 (a) and Fig. 4.14 (b), respectively.


Fig 4.14 (a) Dowel Connectors and Bonding Agent applied on Beam with Smooth Surface


Fig 4.14 (b) Dowel Connectors and Bonding Agent applied on Beam with Chipped Surface

Figure 4.14: Dowel Connectors and Bonding Agent applied on Beam with Smooth Surface and Dowel Connectors and Bonding Agent applied on Beam with Chipped Surface

- **Without Using Dowel Connectors and Bonding Agent and using only Micro-concrete**

This strengthening method requires no use of dowel connectors and bonding agent. Jacketing of the beam is carried out using only micro-concrete. Table 4.5 represents 28 day average cube Strength of Micro-Concrete for 70 mm cube Size.

Table 4.5: Average Cube Strength of Micro-Concrete

| Sr. No | Specimens Notations | Cube strength(MPa) | Avg. Cube Strength (MPa) |
|---|---|---|---|
| 1 | QSD | 59.18, 62.24, 53.06 | 58.16 |
| 2 | QSB | 70.4, 69.38, 65.3 | 68.37 |
| 3 | QSDB | 63.26, 53.06, 57.14 | 57.82 |
| 4 | QSM | 53.06, 53.06, 59.18 | 55.1 |
| 5 | QPD | 47.95, 46.93, 53.06 | 49.32 |
| 6 | QPB | 48.97, 51.02, 47.95 | 49.32 |
| 7 | QPDB | 52.04, 54.08, 48.97 | 51.7 |
| 8 | QPM | 61.22, 62.24, 53.06 | 58.84 |
| 9 | RQSD | 45.91, 47.95,47.95 | 47.28 |
| 10 | RQSB | 54.08, 55.1, 51.02 | 53.4 |
| 11 | RQSDB | 48.97, 47.95, 52.04 | 49.66 |
| 12 | RQSM | 52.04, 51.02, 53.06 | 52.04 |
| 13 | RQPD | 51.02, 50, 44.89 | 48.64 |
| 14 | RQPB | 48.97, 44.89, 54.08 | 49.32 |
| 15 | RQPDB | 50, 47.95, 47.95 | 48.64 |
| 16 | RQPM | 45.91, 46.93, 44.89 | 45.92 |
| | | Total Value (N/mm2) | 52.720625 |

Jacketing techniques without using dowel connectors and bonding agent and using only micro-concrete as applied on smooth surface beam and chipped surface beam is shown in Fig. 4.15 (a) and Fig. 4.15 (b), respectively.

Fig. 4.15(a) No use of Dowel Connectors and Bonding Agent for Micro-concreted Beam with Smooth Surface

Fig. 4.15(b) No use of Dowel Connectors and Bonding Agent for Micro-concreted Beam with chipped Surface

Figure 4.15: No use of Dowel Connectors and Bonding Agent for Micro-concreted Beam with Smooth Surface and No use of Dowel Connectors and Bonding Agent for Micro-concreted Beam with chipped Surface

## 4.5 Procedure for Repair and Strengthening of Beams by use of Various Methods

Two control beams C1 and C2 are tested up to their ultimate load carrying capacity. Remaining eight beams are tested after 28 days of curing up to their ultimate load carrying capacity. The beams are repaired by means of grouting.

For grouting process, drilling is carried out on every crack to facilitate fitting of nozzles. The nozzles are fixed on the beam surface on drilled portion using m-seal on the beam surface. Surrounding parts for nozzles along cracks is sealed by m-seal to prevent leakage of the grouting material. Salbond-RX50 is used as the grouting material. Properties of Salbond-RX50 are given in section 4.3.2. Grouting is conducted for RC beam with smooth and chipped surface, respectively. Fig. 4.16 and 4.17 show step-by-step process of grouting for RC beam. Fig. 4.16 (a) shows Drilling along Crack for fitting of Nozzles. Fig.4.16 (b) shows Fitting of Nozzles and sealing of crack by m-seal.

Fig 4.16 (a) Drilling along Crack for fitting of Nozzles

Fig 4.16 (b) Fitting of Nozzles and Sealing of cracks by m-seal

Figure 4.16: Drilling along Crack for Nozzles fitting and Fitting of Nozzles and Sealing of cracks by m-seal

Fig. 4.17 (a) shows grouting instrument. Fig. 4.17 (b) shows crack filling of beam by grouting, respectively.

Fig 4.17(a) Grouting Instrument


Fig 4.17(b) Crack Filling

Figure 4.17: Grouting Instrument and Crack Filling

For checking effectiveness of grouting for filling up of cracks, Ultrasonic pulse velocity test is conducted on all grouted beams. For testing on beams by U.P.V method, an ultrasonic pulse of longitudinal vibration is produced by an elctro-acoustical transducer which is held in contact with surface of concrete. Proper airtight medium like grease is applied between the transducers and the concrete surface to avoid the entrapment of air. Results of test are noted in the form of pulse velocity. U.P.V test has been conducted using surface transmission method. Velocity criterion for UPV test for quality of concreting is given in the Table 4.6

Table 4.6: Velocity Criterion for Quality Grading of Concreting as per the IS: 13311[3]

| Pulse Velocity (m/s) | Quality of concrete |
|---|---|
| 4500 and above | Excellent |
| 3500 to 4500 | Good |
| 3000 to 3500 | Medium |
| Less than 3000 | Doubtful |

Fig. 4.18 shows instrument used for U.P.V test.


Figure 4.18: Instrument for U.P.V Test

Chipping process is same as discussed section 4.4. Strengthening of grouted beams is done by using same techniques like use of dowel connectors and micro-concrete, bonding agent and micro-concrete, use of dowel connectors and bonding agent with micro-concrete and without using dowel connectors and bonding agent and using only micro-concrete as discussed in section 4.4.

## 4.6 Testing Set-up

All 28 beams are tested at loading frame in structures laboratory. The beams are tested in flexure under two-point loading system. The load is applied using hydraulic jack of 500 kN capacity. Details of test setup are given in Fig 4.19

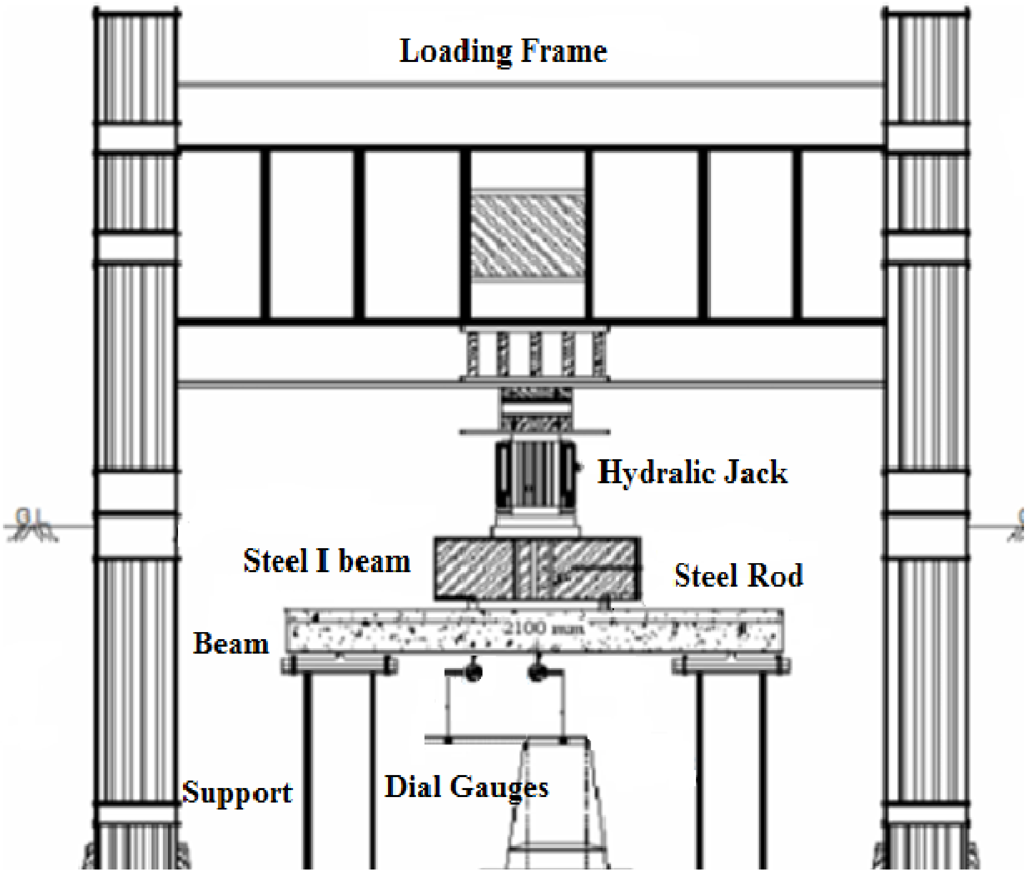



Figure 4.19: Detail of test setup for beam

The load is applied on the beam at mid span of the beam. The load is transferred from the jack to steel I beam and on to the steel rod. The beam is placed simply supported on either side by steel column support as shown. To access the behaviour of the tested beams, the applied load, strains at the external surface of concrete and displacement are measured using instruments such as deflection dial gauge and electrical strain gauges, respectively. Two deflection dial gauges are used to measure the deflection of the RC beam. One dial gauge is placed below tension surface of the beam at mid span. Second dial gauge is placed below tension surface of beam under the point load as shown in Fig. 4.19 Deflection dial gauges are kept in such a way so that it remains in contact with bottom side of tension surface of the beam as shown in Fig. 4.19 Strain measurement is taken on various positions on the beam. Cracking pattern for the specimens is measured. The failure modes of the beams are also studied under various experimental conditions.

## 4.7 Instruments

Load, displacement and strain variation for the beams are measured using hydraulic jack, Deflection dial gauge and electrical strain gauge, respectively. Different instruments used in experimental work are as follows:-

- Hydraulic Jack
- Deflection dial gauge
- Electrical Strain Gauges

### 4.7.1 Hydraulic Jack

Hydraulic jack of capacity of 500 kN is used. It works based on Pascal's principle. Basically, the principle states that the pressure in a closed container is the same at all points. Pressure is described mathematically by a Force divided by Area. Therefore if there are two cylinders connected together, a small one and a large one, and apply force to the small cylinder, this would result in a given pressure. Fig.4.20 shows the hydraulic jack.

Figure 4.20: Hydraulic Jack

### 4.7.2 Deflection Dial Gauge

Dial gauge is used to measure displacement of a beam during the load application. It is fitted in such a way that its needle touches point on beam surface at which the measurement of deflection is required. Dial gauge is used for above application is shown in Fig. 4.21

Figure 4.21: Deflection Dial Gauges

### 4.7.3 Electrical Strain Gauges

The Model P3 Strain Indicator and recorder is used for measuring strain on the entire specimen. Data, recorded at auto mode with rate of up to 1 reading per channel per second as well as manually and is transferred by USB to a computer. Fig. 4.22 shows P3 strain indicator and recorder.


Figure 4.22: P3 Strain Indicator and Recorder

Fig. 4.23 shows the circuit diagram for single active gauge and Fig. 4.24 shows the connections for making a three-wire quarter bridge connection. Bridge completion resistors of 120, 350 and 1000 ohms are built in for quarter-bridge operation. For bridge completion wire of 350 ohms is used for quarter bridge operation.

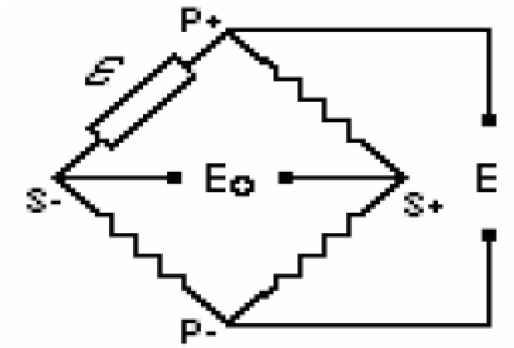



Figure 4.23: Single active gauge in uniaxial tension or compression

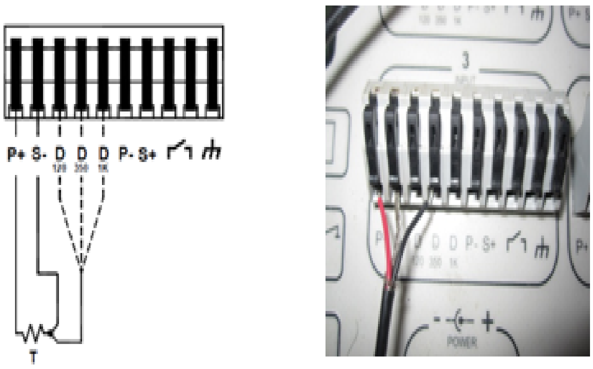



Figure 4.24: P3 Strain Indicator and Recorder

# Chapter 5

# Strengthened Beams

## 5.1 General

Observations recorded during testing of strengthened by employing various jacketing methods beam are discussed. In this chapter deflection and strain at different locations at various load increments is measured and reported. Comparative performance of beams strengthened by various jacketing methods by testing under two point loading condition is assessed. Comparison of failure load, maximum deflection and strain evaluated for strengthened beams has been given in tabular form as well as in form of graphical representation. Behaviour of the jacketed beams has been compared in terms of failure mode and crack pattern.
Parameters compared for strengthened RC beams are as follows:

- Failure load
- Load vs. Displacement
- Load vs. Strain
- Failure mode and Crack Pattern
- Experimental and Analytical Results

For easy understanding of results, meanings of various notations for the beams have been reported as follows.

| Notation | | Description |
|---|---|---|
| Q | = | Strengthened Beam |
| R | = | Repaired Beam |
| C | = | Control Beam |
| S | = | Beam with Smooth Surface and micro-concrete |
| P | = | Beam with Chipped Surface and micro-concrete |
| D | = | Beam with Dowel Connectors and micro-concrete |
| B | = | Beam with Bonding Agent and micro-concrete |
| M | = | Beam without Dowel Connectors and Bonding Agent and with only micro-concrete |

## 5.2 Load Carrying Capacity

Load carrying capacity of strengthened beams is ranging from 260 kN to 300 kN. Experimental load carrying capacity for Strengthened beams is reported in Table 5.1

Table 5.1: Experimental load for Strengthened beams

| Sr. No | Beams Notations | Experimental Failure Load(kN) |
|---|---|---|
| 1 | QSD | 270 |
| 2 | QSB | 260 |
| 3 | QSDB | 290 |
| 4 | QSM | 260 |
| 5 | QPD | 260 |
| 6 | QPB | 295 |
| 7 | QPDB | 290 |
| 8 | QPM | 300 |

Fig. 5.1 shows comparison for load carrying capacity for the strengthened beams.

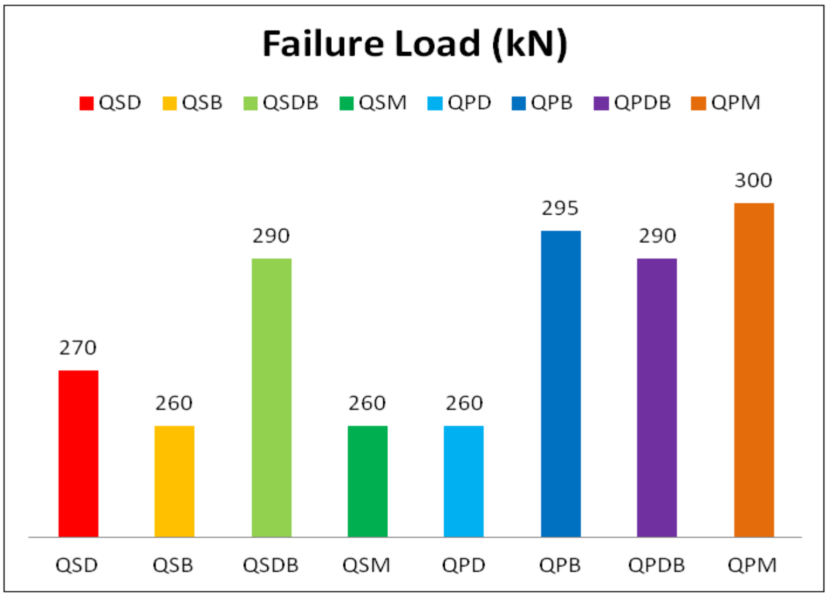



Figure 5.1: Failure Load for Strengthened Beams

Percentage increment in failure load is ranging from 3.84% to 11.53% for smooth surface strengthened beams. Percentage increment in failure load is ranging from 1.69% to 15.38% for chipped surface strengthened beams. Percentage increment in failure load for strengthened beams is presented in Table 5.2

Table 5.2: Percentage Increment in Failure Load for Strengthened Beams

| Beams | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
|---|---|---|---|---|---|---|---|---|
| QSD | 0 | -3.7 | 7.4 | -3.7 | -3.7 | - | - | - |
| QSB | 3.84 | 0 | 11.53 | 0 | - | 13.46 | - | - |
| QSDB | -6.89 | -10.34 | 0 | -10.34 | - | - | 0 | - |
| QSM | 3.84 | 0 | 11.53 | 0 | - | - | - | 15.38 |
| QPD | 3.84 | - | - | - | 0 | 13.46 | 11.53 | 15.38 |
| QPB | - | -11.86 | - | - | -11.86 | 0 | -1.69 | 1.69 |
| QPDB | - | - | 0 | - | -10.34 | 1.72 | 0 | 3.44 |
| QPM | - | - | - | -13.33 | -13.33 | -1.66 | -3.33 | 0 |

For smooth surface beams, failure load of -3.7.%, 7.4.% and -3.7.% has been observed for beams QSB, QSDB and QSM as compared to that of beam QSD. Failure load of 3.8% and 11.53% has been observed for beams QSD and QSDB as compared to that of beam QSB. Failure load carrying capacity of beam QSB and beam QSM has been observed at par. Failure load of -6.89%, -10.34% and -10.34% has been observed for beams QSD, QSB and QSM as compared to that of beam QSDB. Failure load of 3.84% and 11.53% has been observed for beams QSD and QSDB as compared to that of beam QSM. Failure load carrying capacity of beam QSB and beam QSM has been observed at par.

For chipped surface beams, failure load of 13.46.%, 11.53.% and 15.38% has been observed for beams QPB, QPDB and QPM as compared to that of beam QPD. Failure load of -11.86%, -1.69% and 1.69% has been observed for beams QPD, QPDB and QPM as compared to that of beam QPB. Failure load of -10.34%, 1.72% and 3.44% has been observed for beams QPD, QPB and QPM as compared to that of beam QPDB. Failure load of -13.33%, -1.66% and -3.33% has been observed for beams QPD, QPB and QPDB as compared to that of beam QPM.

Comparing performance of smooth surface and chipped surface beams, reduction in failure load of beam 3.7% has been observed for beam QPD as compared to that for beam QSD. Increment in failure load of 13.46% has been observed for beam QPB compared to that for beam QSB. Failure load carrying capacity of beam QPDB and beam QSDB has been observed at par. Increment in failure load of 15.38% has been observed for beam QPM as compared to that for beam QSM.

For smooth surface beam higher load carrying capacity has been observed for beam QSDB as compared to that for beam QSD. This suggests that combined use of dowel connectors and bonding agent with micro-concrete is more effective techniques as compared to other techniques for beams with smooth surface.

For chipped surface beam higher load carrying capacity has been observed for beam QPM as compared to that for beam QPD. For chipped surface strengthened beams use of only micro-concrete without using dowel connectors and bonding agent is more effective jacketing techniques as compared to other techniques used..

## 5.3 Displacement

Displacement is measured at mid span and at point load at bottom side for the strengthened beams at interval of every 10 kN load till the failure of beams. Table 5.3 and 5.4 shows results of displacement for strengthened beams at mid span and at point load at bottom side, respectively.

Table 5.3: Results of Displacement for Strengthened Beams at Mid Span

| Load | Beams Notations (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| kN | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.12 | 0.11 | 0.28 | 0.13 | 0.25 | 0.05 | 0.19 | 0.33 |
| 20 | 0.52 | 0.4 | 0.58 | 0.27 | 0.37 | 0.2 | 0.32 | 0.61 |
| 30 | 0.78 | 0.68 | 0.85 | 0.34 | 0.52 | 0.4 | 0.64 | 0.92 |
| 40 | 1 | 0.98 | 1.14 | 0.45 | 0.75 | 0.6 | 0.77 | 1.13 |
| 50 | 1.47 | 1.2 | 1.41 | 0.62 | 0.92 | 0.84 | 1.01 | 1.33 |
| 60 | 1.7 | 1.48 | 1.6 | 0.77 | 1.02 | 0.95 | 1.25 | 1.52 |
| 70 | 1.91 | 1.8 | 1.81 | 0.92 | 1.2 | 1.1 | 1.46 | 1.72 |
| 80 | 2.18 | 2.02 | 2.16 | 1.07 | 1.25 | 1.23 | 1.64 | 1.97 |
| 90 | 2.43 | 2.45 | 2.55 | 1.22 | 1.32 | 1.36 | 1.78 | 2.22 |
| 100 | 2.69 | 2.87 | 2.78 | 1.47 | 1.5 | 1.51 | 2.04 | 2.51 |
| 110 | 2.91 | 3.08 | 3.16 | 1.69 | 1.65 | 1.7 | 2.24 | 2.71 |
| 120 | 3.21 | 3.4 | 3.58 | 2.12 | 1.9 | 1.85 | 2.46 | 3.01 |
| 130 | 3.51 | 3.8 | 4.35 | 2.32 | 2.05 | 2.08 | 2.71 | 3.34 |
| 140 | 3.96 | 4.1 | 5.31 | 2.62 | 2.31 | 2.3 | 2.94 | 3.62 |
| 150 | 4.29 | 4.32 | 5.5 | 2.92 | 2.7 | 2.7 | 3.19 | 3.9 |
| 160 | 4.83 | 4.7 | 5.58 | 3.12 | 2.9 | 2.85 | 3.45 | 4.21 |
| 170 | 5.13 | 5 | 5.73 | 3.32 | 3.18 | 3.05 | 3.64 | 4.49 |
| 180 | 5.18 | 5.62 | 6.68 | 3.87 | 3.4 | 3.85 | 3.82 | 4.75 |
| 190 | 5.36 | 6.4 | 7.53 | 4.22 | 3.6 | 4.5 | 4.01 | 5.17 |
| 200 | 5.66 | 8.2 | 8.37 | 7.47 | 3.8 | 6.05 | 4.22 | 5.42 |
| 210 | 5.98 | 9.55 | 10.63 | 8.27 | 3.98 | 7.05 | 4.45 | 5.74 |
| 220 | 6.73 | 10.8 | 11.33 | 9.12 | 4.4 | 7.65 | 4.69 | 6.27 |
| 230 | 8.48 | 11.8 | 12.83 | 9.52 | 5.4 | 9 | 4.92 | 7.01 |
| 240 | 10.43 | 12.8 | 17.43 | 10.52 | 6.7 | 9.75 | 5.27 | 8.74 |
| 250 | 19.88 | 14.9 | 22.83 | 12.47 | 11.33 | 15.25 | 6.76 | 9.94 |
| 260 | 26.18 | 17.8 | 25.83 | 21.62 | 12.12 | 15.75 | 7.75 | 12.89 |
| 270 | 32.28 | | 27.43 | | | 16.29 | 8.89 | 15.31 |
| 280 | | | 28.48 | | | 16.6 | 11.24 | 19.89 |
| 290 | | | 30.23 | | | 17.23 | 13.74 | 25.04 |
| 300 | | | | | | 20.63 | | 28.39 |

Table 5.4: Results of Displacement for Strengthened Beams at Point Load

| Load | Specimens Notations (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.08 | 0.07 | 0.19 | 0.13 | 0.45 | 0.04 | 0.18 | 0.05 |
| 20 | 1.47 | 0.34 | 0.44 | 0.16 | 0.58 | 0.18 | 0.28 | 0.38 |
| 30 | 1.7 | 0.5 | 0.66 | 0.2 | 0.7 | 0.31 | 0.48 | 0.64 |
| 40 | 1.9 | 0.75 | 0.88 | 0.27 | 0.87 | 0.48 | 0.64 | 0.8 |
| 50 | 3.2 | 0.89 | 1.12 | 0.37 | 1.02 | 0.68 | 0.82 | 0.97 |
| 60 | 3.38 | 1.11 | 1.26 | 0.47 | 1.1 | 0.77 | 1.01 | 1.12 |
| 70 | 3.54 | 1.37 | 1.36 | 0.57 | 1.31 | 0.89 | 1.17 | 1.26 |
| 80 | 3.79 | 1.55 | 2.66 | 0.71 | 1.37 | 1.03 | 1.31 | 1.44 |
| 90 | 3.96 | 1.89 | 2.97 | 0.84 | 1.42 | 1.13 | 1.42 | 1.63 |
| 100 | 4.27 | 2.27 | 3.16 | 1.05 | 1.57 | 1.28 | 1.63 | 1.82 |
| 110 | 4.47 | 2.42 | 3.46 | 1.25 | 1.7 | 1.41 | 1.79 | 1.93 |
| 120 | 4.71 | 2.68 | 3.86 | 1.55 | 1.92 | 1.55 | 1.98 | 2.21 |
| 130 | 4.96 | 3.02 | 4.49 | 1.75 | 2.04 | 1.74 | 2.2 | 2.48 |
| 140 | 5.34 | 3.27 | 5.22 | 2 | 2.3 | 1.93 | 2.39 | 2.68 |
| 150 | 5.64 | 3.47 | 5.94 | 2.27 | 2.63 | 2.23 | 2.61 | 2.9 |
| 160 | 6.27 | 3.82 | 6.04 | 2.45 | 2.82 | 2.38 | 2.83 | 3.14 |
| 170 | 6.24 | 4.07 | 6.19 | 2.63 | 3.06 | 2.58 | 2.98 | 3.35 |
| 180 | 6.29 | 4.62 | 6.89 | 2.97 | 3.28 | 3.28 | 3.13 | 3.57 |
| 190 | 6.45 | 5.2 | 7.64 | 3.42 | 3.47 | 3.71 | 3.29 | 3.82 |
| 200 | 6.69 | 7.57 | 8.94 | 5.1 | 3.65 | 4.98 | 3.46 | 4.12 |
| 210 | 6.99 | 8.52 | 10.04 | 5.8 | 3.9 | 5.83 | 3.66 | 4.36 |
| 220 | 7.34 | 8.94 | 10.64 | 6.5 | 4.21 | 6.18 | 3.84 | 4.77 |
| 230 | 8.79 | 9.67 | 11.74 | 6.83 | 5.22 | 8.13 | 4.03 | 5.37 |
| 240 | 11.09 | 10.47 | 14.94 | 7.58 | 6.27 | 8.68 | 4.31 | 5.67 |
| 250 | 15.54 | 12.67 | 18.79 | 10.15 | 10.37 | 11.98 | 5.28 | 7.02 |
| 260 | 20.24 | 15.02 | 21.14 | 13.4 | 10.72 | 12.18 | 5.95 | 8.83 |
| 270 | 25.39 | | 21.64 | | | 12.33 | 6.77 | 10.8 |
| 280 | | | 22.54 | | | 12.52 | 8.61 | 14.12 |
| 290 | | | 25.34 | | | 13.63 | 10.72 | 18.27 |
| 300 | | | | | | 16.93 | | 21.2 |

Load verses displacement relationship for strengthened beams at mid span and at point load below bottom side are presented in Fig. 5.2 and Fig. 5.3, respectively.

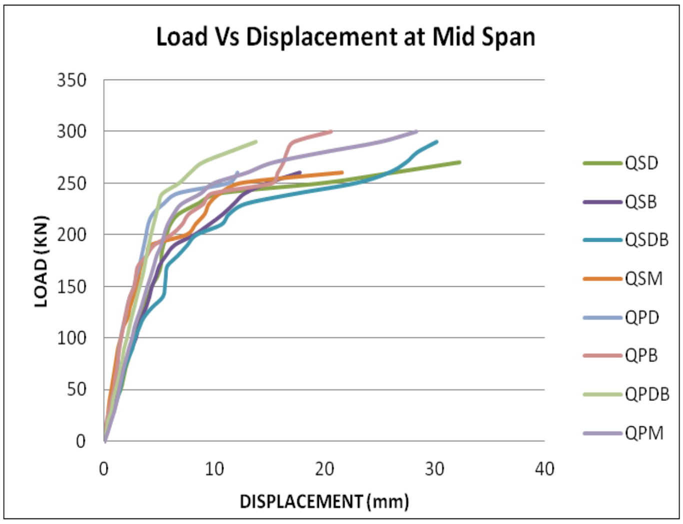



Figure 5.2: Load-Displacement relationship at Mid Span for Strengthened Beams

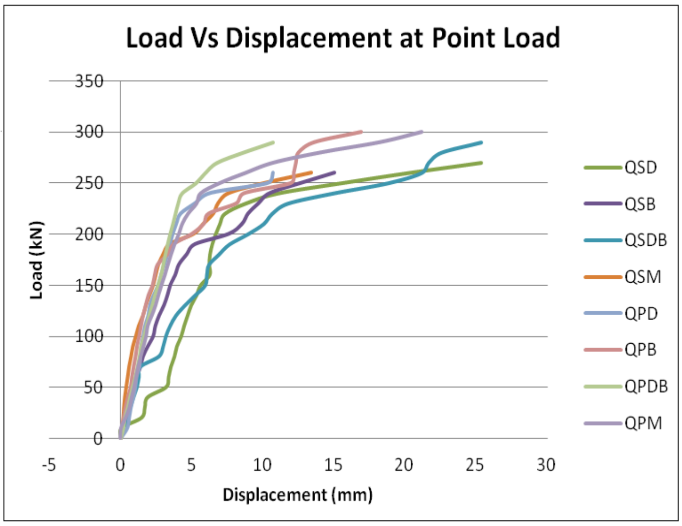



Figure 5.3: Load-Displacement relationship at Point Load for Strengthened Beams

Percentage increment in displacement at mid span is ranging from 6.78 % to 81.34 % for smooth surface strengthened beams. Percentage increment in displacement at mid span is ranging from 13.36 % to 134.24 % for chipped surface strengthened beams.Percentage increment in displacement at mid span for strengthened beams is presented in table 5.5.

Table 5.5: Percentage Increment in Displacement at Mid Span for Strengthened Beams

| Beams | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
|---|---|---|---|---|---|---|---|---|
| QSD | 0 | -44.85 | -6.35 | -33.02 | -62.45 | - | - | - |
| QSB | 81.34 | 0 | 69.83 | 21.46 | - | 15.89 | - | - |
| QSDB | 6.78 | -41.11 | 0 | -28.48 | - | - | -54.54 | - |
| QSM | 49.3 | -17.66 | 39.82 | 0 | - | - | - | 31.31 |
| QPD | 166.33 | - | - | - | 0 | 70.21 | 13.36 | 134.24 |
| QPB | - | -13.71 | - | - | -41.25 | 0 | -33.39 | 37.61 |
| QPDB | - | - | 120.01 | - | -11.79 | 50.14 | 0 | 106.62 |
| QPM | - | - | - | -23.84 | -57.3 | -27.33 | -51.6 | 0 |

For smooth surface beams, displacement at mid span of -44.85 %, -6.35 % and -33.02 % has been observed for beams QSB, QSDB and QSM as compared to that of beam QSD. Displacement at mid span of 81.34 %, 69.83 % and 21.48 % has been observed for beams QSD, QSDB and QSM as compared to that of beam QSB. Displacement at mid span of 6.78 %, -41.11 % and -28.48 % has been observed for beams QSD, QSB and QSM as compared to that of beam QSDB. Displacement at mid span of 49.3 %, -17.66 % and 39.82 % has been observed for beams QSD, QSB and QSDB as compared to that of beam QSM.

For chipped surface beams, Displacement at mid span of 70.21 %, 13.36 % and 134.24 % has been observed for beams QPB, QPDB and QPM as compared to that of beam QPD. Displacement at mid span of -41.25 %, -33.39 % and 37.6 %1 has been observed for beams QPD, QPDB and QPM as compared to that of beam QPB. Displacement at mid span of -11.79 %, 50.14 % and 103.62 % has been observed for beams QPD, QPB and QPM as compared to that of beam QSDB. Displacement at mid span of -57.3 %, -27.33 % and -51.6 % has been observed for beams QSD, QPB and QPDB as compared to that of beam QPM.

Comparing performance of smooth surface and chipped surface beams, reduction in displacement at mid span of beam 62.45 % has been observed for beam QPD as compared to that for beam QSD. Increment in displacement at mid span of 15.89 % has been observed for beam QPB compared to that for beam QSB. Decrement in displacement at mid span of 54.54 % has been observed for beam QPDB as compared to that for beam QSDB. Increment in displacement at mid span of 31.31 % has been observed for beam QPM compared to that for beam QSM.

For smooth surface beam, at higher load higher displacement of beam QSDB and beam QSD has been observed at par. This suggests that combined use of dowel connectors and bonding agent with micro-concrete is more effective techniques as compared to other techniques for beams with smooth surface.

For chipped surface beam, at higher load higher displacement of beam QPM and beam QSD has been observed. This suggest that for chipped surface strengthened beams use of only micro-concrete without using dowel connectors and bonding agent is more effective jacketing techniques as compared to other techniques used.

## 5.4 Strain

Strain in concrete at four different positions has been measured for the beams. Positions 1, 2, 3 and 4 indicate the locations at which the strain in concrete has been evaluated for the beams as given in Fig. 5.4

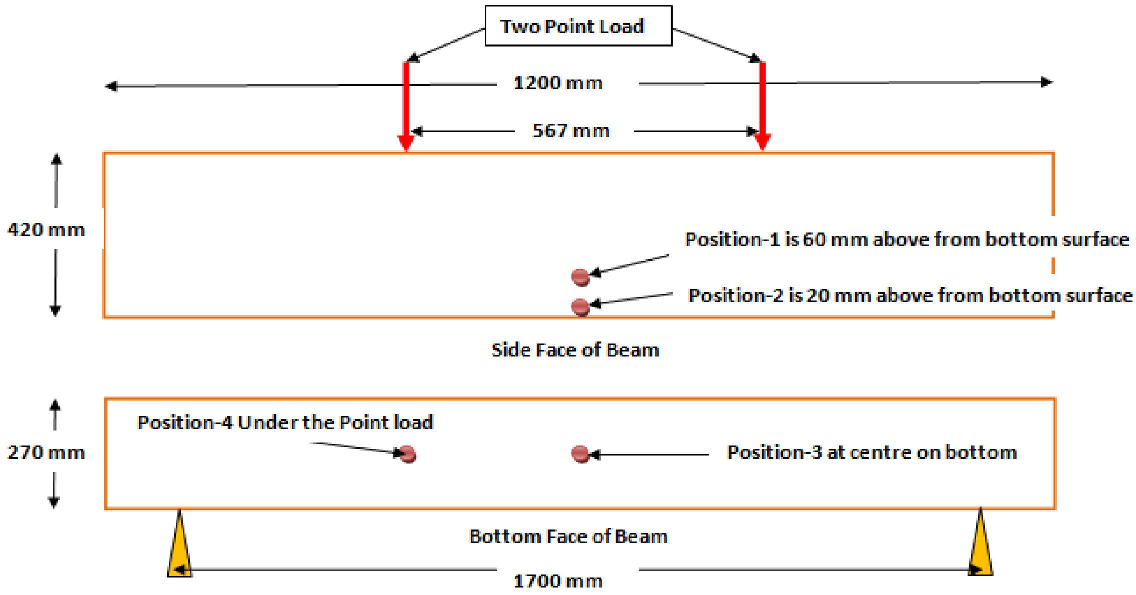



Figure 5.4: Location of Strain Gauges on Beam

Position-1 indicates strain in concrete evaluated at location above 60 mm from bottom surface of the beam. Results are presented in table5.6 for the strengthened beams. Position-2 indicates results of strain in concrete measured at 20 mm above from bottom surface. Corresponding results of strain are presented in table 5.7. Position-3 indicates results of strain in concrete at mid span at bottom surface for the strengthened beams. The results of strain are presented in table 5.8. Position-4 indicates strain in concrete under point load on bottom surface in table 5.9 for the beams. The corresponding results are given in table5.9.

Table 5.6: Strain at Position-1 for Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | -0.00004 | 0.00004 | -0.00001 | -0.00001 | -0.00003 | -0.00003 | 0.00025 | 0.00001 |
| 20 | -0.00006 | 0.00004 | 0.00024 | -0.00001 | 0.00002 | -0.00005 | 0.00074 | 0.00002 |
| 30 | -0.00007 | 0.00006 | 0.00051 | -0.00001 | 0.00001 | -0.00005 | 0.00111 | 0.00002 |
| 40 | -0.00007 | 0.00007 | 0.00068 | -0.00001 | 0.00003 | -0.00006 | 0.00222 | 0.00003 |
| 50 | -0.00002 | 0.00007 | 0.00119 | -0.00001 | -0.00002 | -0.00004 | 0.00272 | 0.00003 |
| 60 | -0.00005 | 0.00009 | 0.0016 | -0.00001 | 0.00002 | -0.00002 | 0.00247 | 0.00002 |
| 70 | -0.00005 | 0.00011 | 0.00204 | -0.00001 | 0 | 0 | 0.00226 | 0.00001 |
| 80 | -0.00006 | 0.00012 | 0.00292 | -0.00001 | -0.00003 | 0.00002 | 0.00236 | -0.00002 |
| 90 | -0.00002 | 0.00013 | 0.0037 | -0.00001 | 0 | 0.00006 | 0.00227 | -0.00003 |
| 100 | -0.00005 | 0.00014 | 0.00473 | -0.00002 | -0.00002 | 0.00012 | 0.00222 | -0.00004 |
| 110 | -0.00009 | 0.00014 | 0.00907 | -0.00002 | -0.00003 | 0.0002 | 0.00224 | -0.00004 |
| 120 | -0.00011 | 0.00016 | 0.01495 | -0.00002 | -0.00003 | 0.00019 | 0.00241 | -0.00003 |
| 130 | -0.00007 | 0.00019 | 0.01751 | 0.00046 | -0.00001 | 0.00012 | 0.00267 | -0.00003 |
| 140 | -0.00013 | 0.00021 | 0.01442 | 0.0005 | -0.00004 | 0.00012 | 0.00287 | -0.00002 |
| 150 | -0.00009 | 0.00023 | 0.01269 | 0.00059 | 0.00003 | 0.00013 | 0.00282 | -0.00002 |
| 160 | -0.00013 | 0.00036 | 0.01304 | 0.00058 | -0.00001 | 0.00009 | 0.00281 | -0.00001 |
| 170 | -0.00014 | 0.00036 | 0.01216 | 0.00055 | -0.00005 | 0.00006 | 0.00336 | 0 |
| 180 | -0.00011 | 0.00038 | 0.01232 | 0.00051 | 0 | 0.00005 | 0.00346 | 0.00001 |
| 190 | -0.00007 | 0.00038 | 0.01216 | 0.00051 | 0.00001 | -0.00011 | 0.00355 | 0.00001 |
| 200 | -0.00009 | 0.00041 | 0.01247 | 0.00047 | -0.00002 | -0.00011 | 0.00362 | 0.00002 |
| 210 | -0.00011 | 0.00042 | 0.01226 | 0.00042 | 0.00001 | -0.00008 | 0.00369 | 0.00002 |
| 220 | -0.00011 | 0.00042 | 0.0126 | 0.00032 | -0.00001 | -0.0001 | 0.00393 | 0.00004 |
| 230 | -0.00001 | 0.00044 | 0.01277 | 0.00038 | 0 | -0.00007 | 0.00422 | 0.00034 |
| 240 | 0.00002 | 0.00044 | | 0.00034 | 0.00001 | -0.00022 | 0.00439 | 0.00148 |
| 250 | 0.00003 | 0.00043 | | 0.00037 | -0.00002 | -0.00024 | 0.00454 | 0.00171 |
| 260 | 0.0002 | 0.00047 | | 0.00044 | -0.00002 | -0.00025 | 0.00496 | 0.00204 |
| 270 | 0.00051 | | | | | -0.00025 | 0.00504 | |
| 280 | | | | | | -0.00025 | 0.00527 | |
| 290 | | | | | | -0.00026 | 0.00562 | |

Table 5.7: Strain at Position-2 Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.00009 | -0.00001 | 0.00005 | -0.00001 | 0.00028 | 0.00002 | 0.00002 | 0.00001 |
| 20 | 0.00011 | -0.00001 | 0.00009 | 0 | 0.00013 | 0.00012 | 0.00004 | 0.00002 |
| 30 | 0 | -0.00001 | 0.00015 | 0 | -0.00014 | 0.00028 | 0.00005 | 0.00003 |
| 40 | -0.00003 | -0.00001 | 0.00031 | 0 | 0.00004 | 0.00072 | 0.00006 | 0.00005 |
| 50 | -0.00011 | -0.00002 | 0.00042 | 0.00001 | 0.00009 | 0.00196 | 0.00008 | 0.00005 |
| 60 | -0.00002 | -0.00001 | 0.00106 | 0.00001 | 0.00009 | 0.00272 | 0.00009 | 0.00006 |
| 70 | -0.00009 | -0.00001 | 0.00149 | 0.00001 | 0.00001 | 0.00358 | 0.00011 | 0.00005 |
| 80 | -0.00014 | -0.00001 | 0.00233 | 0 | 0.00023 | 0.00446 | 0.00013 | 0.00001 |
| 90 | -0.00033 | -0.00001 | 0.00401 | 0.00001 | -0.00001 | 0.00556 | 0.00014 | 0.00001 |
| 100 | -0.00052 | -0.00002 | 0.00526 | 0.00001 | 0.00001 | 0.00679 | 0.00016 | 0.00001 |
| 110 | -0.00053 | -0.00001 | 0.01282 | 0.00002 | -0.00006 | 0.00816 | 0.00017 | 0.00006 |
| 120 | -0.00067 | -0.00002 | 0.00484 | 0.00004 | 0.00005 | 0.0095 | 0.00019 | 0.0001 |
| 130 | -0.00066 | -0.00002 | | 0.00001 | 0 | 0.00939 | 0.0002 | 0.00017 |
| 140 | -0.00089 | -0.00002 | | 0.00003 | 0.00023 | 0.01013 | 0.00021 | 0.0002 |
| 150 | -0.00093 | -0.00002 | | 0.00003 | 0.00006 | 0.01179 | 0.00021 | 0.00029 |
| 160 | -0.00118 | -0.00005 | | 0.00003 | 0.00022 | 0.01187 | 0.00021 | 0.00041 |
| 170 | -0.00112 | -0.00004 | | 0.00003 | 0.00008 | 0.01225 | 0.00023 | 0.00033 |
| 180 | -0.00121 | -0.00004 | | 0.00003 | 0.00005 | 0.01338 | 0.00024 | 0.00042 |
| 190 | -0.00128 | -0.00005 | | 0.00003 | -0.00018 | 0.00502 | 0.00025 | 0.00048 |
| 200 | -0.00127 | | | 0.00003 | -0.00009 | 0.00504 | 0.00025 | 0.0005 |
| 210 | -0.00143 | | | 0.00002 | 0.00009 | 0.0059 | 0.00026 | 0.00041 |
| 220 | -0.00264 | | | 0.00002 | 0.00009 | 0.00598 | 0.00027 | 0.00105 |
| 230 | -0.00312 | | | 0.00003 | 0.00001 | 0.00273 | 0.00029 | 0.00216 |
| 240 | -0.00389 | | | 0.00003 | 0 | 0.00152 | 0.0003 | 0.00267 |
| 250 | -0.00523 | | | 0.00002 | 0.0001 | 0.00273 | 0.00032 | 0.00277 |
| 260 | -0.00688 | | | 0.00022 | -0.00001 | 0.00246 | 0.00033 | 0.00282 |
| 270 | -0.00837 | | | | | 0.00219 | 0.00033 | 0.00302 |
| 280 | | | | | | 0.00216 | 0.00033 | 0.00312 |
| 290 | | | | | | 0.00194 | 0.00036 | 0.00017 |
| 300 | | | | | | | 0.00087 | |

Table 5.8: Strain at Position-3 for Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.00029 | 0 | -0.00002 | -0.00001 | 0 | -0.00004 | -0.00003 | -0.00001 |
| 20 | 0.00009 | 0 | 0 | -0.00002 | -0.00003 | -0.00006 | -0.00004 | -0.00001 |
| 30 | 0.00017 | 0 | -0.00001 | -0.00002 | 0 | -0.00006 | -0.00005 | -0.00002 |
| 40 | 0.00026 | 0 | 0 | -0.00001 | -0.00002 | -0.00007 | -0.00006 | -0.00002 |
| 50 | 0.0002 | 0 | -0.00001 | -0.00002 | 0.00009 | -0.00008 | -0.00006 | -0.00002 |
| 60 | 0.00024 | 0.00001 | 0.00001 | -0.00003 | 0.00009 | -0.00009 | -0.00007 | -0.00003 |
| 70 | 0.00031 | 0.00001 | 0.00002 | -0.00003 | 0.00021 | -0.0001 | -0.00007 | -0.00003 |
| 80 | 0.00016 | 0.00001 | 0.00004 | -0.00003 | 0.00033 | -0.00011 | -0.00008 | -0.00001 |
| 90 | 0.00025 | 0.00001 | 0.00004 | -0.00004 | 0.00034 | -0.00012 | -0.00008 | -0.00003 |
| 100 | 0.00029 | 0.00001 | 0.00003 | -0.00004 | 0.00053 | -0.00012 | -0.00009 | -0.00005 |
| 110 | -2.00E-05 | 0.00001 | 0.00013 | -0.00005 | 0.00064 | -0.00013 | -0.00009 | -0.00007 |
| 120 | 0.00024 | 0.00001 | 0.00002 | -0.00005 | 0.00048 | -0.00014 | -0.00009 | -0.00011 |
| 130 | 0.00003 | 0.00001 | -0.00001 | -0.00006 | 0.00044 | -0.00014 | -0.00008 | -0.00014 |
| 140 | 4.00E-05 | 0.00001 | -0.00004 | -0.00007 | 0.00045 | -0.00015 | -0.00009 | -0.00016 |
| 150 | 0 | 0.00001 | -0.00004 | -0.00007 | 0.0003 | -0.00016 | -0.0001 | -0.00016 |
| 160 | 0.00008 | 0.00002 | -0.00005 | -0.00008 | 0.00034 | -0.00017 | -0.0001 | -0.00015 |
| 170 | 0.00017 | 0.00001 | -0.00007 | -0.00007 | 0.0003 | -0.00018 | -0.00015 | -0.00016 |
| 180 | 0.0002 | 0.00001 | -0.00007 | -0.00008 | 0.00025 | -0.00019 | -0.00015 | -0.00016 |
| 190 | 0 | 0.00001 | -0.00006 | -0.00008 | 0.00023 | -0.00023 | -0.00015 | -0.00016 |
| 200 | 0.00006 | 0.00001 | -0.00003 | -0.00008 | 0.00029 | -0.00025 | -0.00015 | -0.00016 |
| 210 | -2.00E-05 | 0.00002 | -0.00005 | -0.00008 | 0.00023 | -0.00025 | -0.00015 | -0.00014 |
| 220 | 0.00009 | 0.00001 | -0.00003 | -0.00008 | 0.00021 | -0.00026 | -0.00015 | -0.00014 |
| 230 | 0 | 0.00002 | -0.00005 | -0.00008 | 0.00019 | -0.00026 | -0.00016 | -0.00013 |
| 240 | 0.00011 | 0.00002 | -0.00003 | -0.00008 | 0.00007 | -0.00027 | -0.00016 | -0.00005 |
| 250 | 0.00019 | 0.00001 | 0.00002 | -0.00009 | 0.0001 | -0.00027 | -0.00016 | -0.00001 |
| 260 | 0.00025 | 0.00003 | 0.00001 | -0.00009 | 0.00014 | -0.00027 | -0.00018 | -0.00002 |
| 270 | 0.00011 | | 0.00001 | 0.00014 | | -0.00028 | -0.00018 | -0.00007 |
| 280 | | | 0.00002 | 0.00011 | | -0.00028 | -0.00018 | 0.00003 |
| 290 | | | | | | -0.00031 | -0.00018 | 0.0001 |
| 300 | | | | | | | -0.00019 | |

Table 5.9: Strain at Position-4 for Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | QSD | QSB | QSDB | QSM | QPD | QPB | QPDB | QPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 10 | 0.00001 | -0.00002 | -0.00015 | 0 | -0.00003 | -0.00006 | 0 | -0.00004 |
| 20 | -0.00004 | -0.00003 | -0.00001 | -0.00001 | -0.00005 | -0.00007 | 0 | -0.00031 |
| 30 | -0.00008 | -0.00003 | -0.00022 | -0.00001 | 0.00001 | -0.00008 | 0 | -0.00003 |
| 40 | -0.00009 | -0.00003 | -0.00001 | -0.00002 | -0.00003 | -0.00009 | -0.00001 | -0.00002 |
| 50 | -0.00003 | -0.00004 | -0.00013 | -0.00002 | -0.00002 | -0.0001 | -0.00001 | -0.00016 |
| 60 | -0.00001 | -0.00004 | 0.00003 | -0.00002 | -0.00005 | -0.00011 | -0.00001 | -0.00047 |
| 70 | -0.00004 | -0.00004 | -0.00004 | -0.00002 | -0.00005 | -0.00012 | -0.00001 | -0.00081 |
| 80 | 0.00011 | -0.00004 | -0.00012 | -0.00002 | -0.00001 | -0.00013 | -0.00002 | -0.00111 |
| 90 | 0.00038 | -0.00004 | -0.00007 | -0.00003 | -0.00002 | -0.00013 | -0.00002 | -0.00143 |
| 100 | 0.00152 | -0.00004 | -0.00013 | -0.00003 | 0.00001 | -0.00016 | -0.00002 | -0.0017 |
| 110 | 0.00283 | -0.00004 | -0.00025 | -0.00003 | -0.00002 | -0.00016 | -0.00002 | -0.00187 |
| 120 | 0.00479 | -0.00004 | -0.00028 | -0.00003 | 0 | -0.00017 | -0.00002 | -0.00208 |
| 130 | 0.0068 | -0.00004 | -0.00028 | -0.00004 | -0.00001 | -0.00019 | -0.00003 | -0.00225 |
| 140 | 0.00835 | -0.00004 | -0.00017 | -0.00004 | -0.00002 | -0.00021 | -0.00002 | -0.00253 |
| 150 | 0.00516 | -0.00004 | -0.00014 | -0.00003 | -0.00001 | -0.00024 | -0.00003 | -0.00262 |
| 160 | -0.00001 | -0.00005 | -0.0001 | -0.00004 | -0.00001 | -0.00027 | -0.00003 | -0.00275 |
| 170 | -0.00008 | -0.00006 | -0.00027 | -0.00004 | -0.00003 | -0.00026 | -0.00006 | -0.00333 |
| 180 | -0.00008 | -0.00006 | -0.00031 | -0.00004 | -0.00003 | -0.00026 | -0.00006 | -0.00339 |
| 190 | -0.00004 | -0.00005 | -0.00013 | -0.00004 | 0.00001 | -0.00032 | -0.00006 | -0.00346 |
| 200 | 0 | -0.00005 | -0.00028 | -0.00005 | 0.00002 | -0.00032 | -0.00006 | -0.00353 |
| 210 | -0.00008 | -0.00005 | -0.00012 | -0.00006 | -0.00004 | -0.00032 | -0.00006 | -0.00361 |
| 220 | -0.00013 | -0.00006 | -0.00028 | -0.00006 | -0.00003 | -0.00033 | -0.00006 | -0.00365 |
| 230 | -0.0001 | -0.00005 | -0.0003 | -0.00007 | 0.00002 | -0.00034 | -0.00006 | -0.00362 |
| 240 | -0.00014 | -0.00005 | -0.00031 | -0.00006 | -0.00001 | -0.00035 | -0.00006 | -0.0036 |
| 250 | -0.00016 | -0.00005 | -0.00018 | -0.00006 | -0.00003 | -0.00035 | -0.00006 | -0.00365 |
| 260 | -0.00015 | -0.00005 | -0.00016 | -0.00007 | 0.00002 | -0.00036 | -0.00007 | -0.00376 |
| 270 | -0.00013 | | -0.00031 | | | -0.00036 | -0.00007 | -0.00444 |
| 280 | | | -0.00019 | | | -0.00037 | -0.00007 | -0.00407 |
| 290 | | | | | | -0.00037 | -0.00008 | -0.00386 |
| 300 | | | | | | | -0.00009 | |

Fig. 5.5 show load vs strain variation in concrete evaluated at positon-1 for strengthened RC beams.

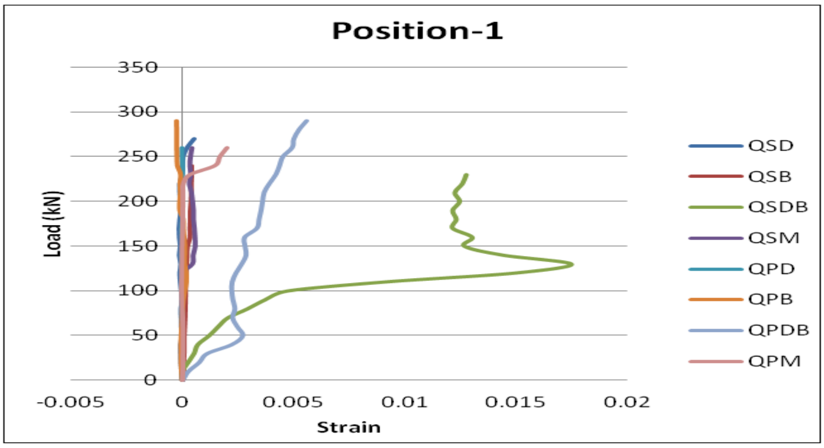



Figure 5.5: Load vs Strain Variation in Concrete evaluated at Positon-1 for Strengthened RC Beams

Fig. 5.6 show load vs strain variation in concrete evaluated at positon-2 for strengthened RC beams.

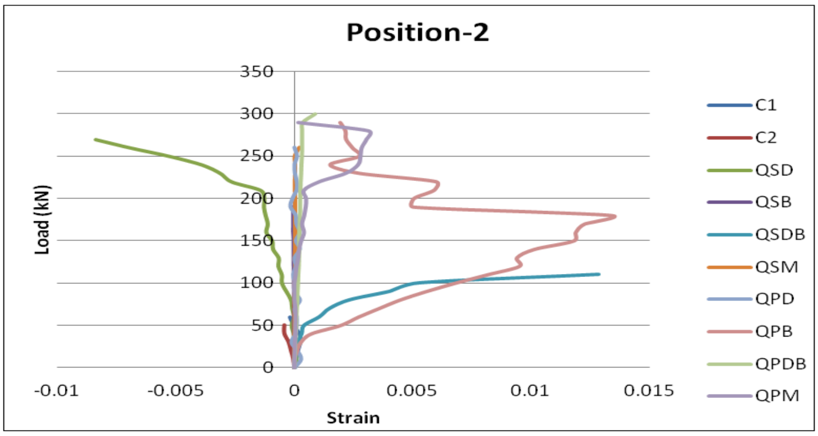



Figure 5.6: Load vs Strain Variation in Concrete evaluated at Positon-2 for Strengthened RC Beams

Fig. 5.7 show load vs strain variation in concrete evaluated at positon-3 for strengthened RC beams.

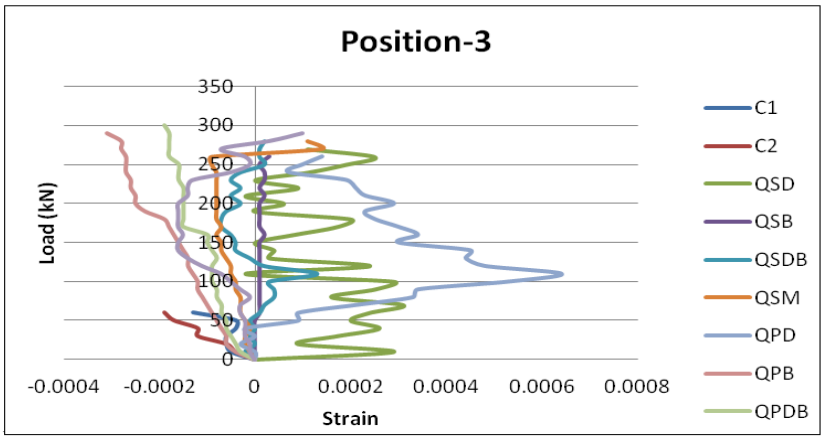



Figure 5.7: Load vs Strain Variation in Concrete evaluated at Positon-3 for Strengthened RC Beams

Fig. 5.8 show load vs strain variation in concrete evaluated at positon-4 for strengthened RC beams.

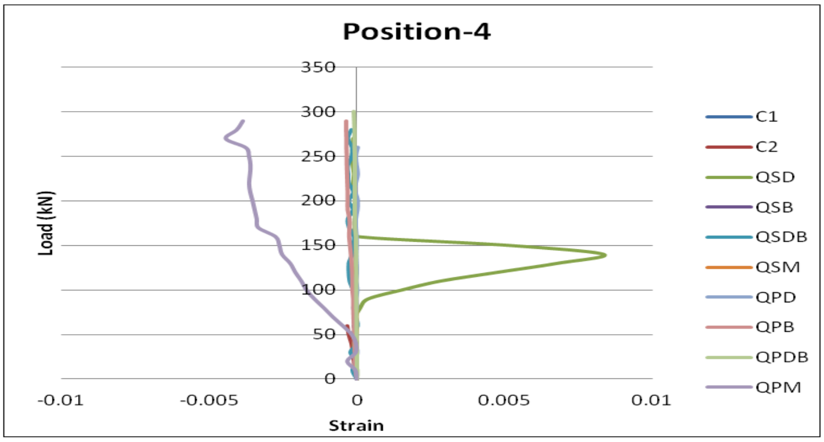



Figure 5.8: Load vs Strain Variation in Concrete evaluated at Positon-4 for Strengthened RC Beams

Maximum Strain has been observed for beams QSDB, QPDB and QPM as compared to beam QSD for all the positions. Higher strain is observed due to bonding between new concrete and old concrete. Good bonding has been observed due to effectiveness of combined use of dowel connectors and bonding agent for the smooth surface beams. For chipped surface beam only micro-concrete is to be observed more effective as compared to that for dowel connectors and bonding agent, respectively.

## 5.5 Failure Mode and Crake Pattern

Initial cracks are observed between 150 kN to 210 kN load for strengthened beams. Cracks are observed in pure bending portion for the beam. Most of cracks are seen on majority occasions in middle third portion. For the beams continuous cracks are observed on bottom face of the beams. At the time of failure cracks are observed up to top bonding plane of old to new concrete for the beams. Maximum crack widths in range of 8mm to 10mm have been observed for beams QSDB and QPM at the failure load. Fig. 5.9(a) and Fig. 5.9(b) show crack pattern and failure mode for beam QSD, respectively.

(a) Crack Pattern for Beam QSD (b) Failure Mode for Beam QSD

Figure 5.9: Crack pattern and Failure mode of beam QSD

Fig. 5.10 (a) and Fig. 5.10 (b) show crack pattern and failure mode of beam QSB, respectively.

(a) Crack Pattern for Beam QSB (b) Failure Mode for Beam QSB

Figure 5.10: Crack pattern and Failure mode of beam QSB

Fig. 5.11 (a) and Fig. 5.11 (b) show crack pattern and failure mode of beam QSDB, respectively.

(a) Crack Pattern for Beam QSDB (b) Failure Mode for Beam QSDB

Figure 5.11: Crack pattern and Failure mode of beam QSDB

Fig. 5.12 (a) and Fig. 5.12 (b) show crack pattern and failure mode of beam QSM, respectively.

(a) Crack Pattern for Beam QSM (b) Failure Mode for Beam QSM

Figure 5.12: Crack pattern and Failure mode of beam QSM

Fig. 5.13 (a) and Fig. 5.13 (b) show crack pattern and failure mode of beam QPD, respectively.

(a) Crack Pattern for Beam QPD (b) Failure Mode for Beam QPD

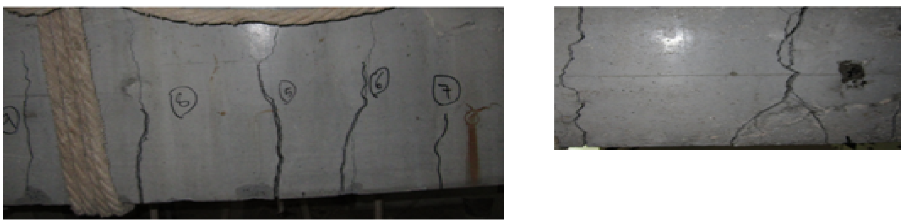
Figure 5.13: Crack pattern and Failure mode of beam QPD

Fig. 5.14 (a) and Fig. 5.14 (b) show crack pattern and failure mode of beam QPB, respectively.

(a) Crack Pattern for Beam QPB (b) Failure Mode for Beam QPB

Figure 5.14: Crack pattern and Failure mode of beam QPB

Fig. 5.15 (a) and Fig. 5.15 (b) show crack pattern and failure mode of beam QPDB, respectively.



(a) Crack Pattern for Beam QPDB (b) Failure Mode for Beam QPDB

Figure 5.15: Crack pattern and Failure mode of beam QPDB

Fig. 5.16 (a) and Fig. 5.16 (b) show crack pattern and failure mode of beam QPM, respectively.

(a) Crack Pattern for Beam QPM

(b) Failure Mode for Beam QPM

Figure 5.16: Crack pattern and Failure mode of beam QPM

## 5.6 Comparison with Analytical Results

Experimental and analytical results for load carrying capacity for strengthened beams are compared in table 5.10

Table 5.10: Experimental and Analytical Results for Load for strengthened Beams

| Sr. No | Specimens Notations | Experimental Failure Load (kN) | Analytical Failure Load (kN) |
|---|---|---|---|
| 1 | QSD | 270 | 165.87 |
| 2 | QSB | 260 | 166.41 |
| 3 | QSDB | 290 | 165.85 |
| 4 | QSM | 260 | 165.67 |
| 5 | QPD | 260 | 165.22 |
| 6 | QPB | 295 | 165.22 |
| 7 | QPDB | 290 | 165.42 |
| 8 | QPM | 300 | 165.92 |

For smooth surface beams, increment of experimental load of 62.77 % has been observed for beam QSD as compared to that of analytical load. Increment of experimental load of 56.24 % has been observed for beam QSB as compared to that of analytical load. Increment of experimental load of 74.86 % has been observed for beam QSDB as compared to that of analytical load. Increment of experimental load of 56.94 % has been observed for beam QSM as compared to that of analytical load.

For chipped surface beams, increment of experimental load of 57.37 % has been observed for beam QPD as compared to that of analytical load. Increment of experimental load of 78.55 % has been observed for beam QPB as compared to that of analytical load. Increment of experimental load of 75.31 % has been observed for beam QPDB as compared to that of analytical load. Increment of experimental load of 80.81 % has been observed for beam QPM as compared to that of analytical load.

For beams with smooth surface, highest failure load of 290 kN is observed for beam QSDB due to combined use of dowel connectors and bonding agent with micro-concrete as compared to that for other jacketing techniques.

For beams with chipped surface, highest failure load of 300 kN is observed for beam QPM due only micro-concrete without dowel connectors and bonding agent as compared to that for other jacketing techniques.

# Chapter 6

# Repaired and Strengthened Beams

## 6.1 General

Observations recorded during testing of repaired and strengthened by employing various jacketing methods beam are discussed. In this chapter deflection and strain at different locations at various load increments is measured and reported. Comparative performance of beams repaired by grouting and strengthened by various jacketing methods by testing under two point loading condition is assessed. Comparison of failure load, maximum deflection and strain evaluated for repaired and strengthened beams has been given in tabular form as well as in form of graphical representation. Behaviour of the jacketed beams has been compared in terms of failure mode and crack pattern.

Parameters compared for repaired and strengthened RC beams are as follows:

Following parameters compared for strengthened RC beams in flexure:

- Failure load
- Load vs. Displacement

- Load vs. Strain
- Failure mode and Crack Pattern
- Experimental and Analytical Results

For easy understanding of results, meanings of various notations for the beams have been reported as follows.

## 6.2 U.P.V Results

The quality of concrete is measured by the ultra sonic pulse velocity (UPV) test. Results of quality of concrete before and after grouting are given in table 6.1 below.

Table 6.1: U.P.V Results of Concrete before and after Grouting [3]

| Sr No. | Notations | Pulse Velocity (m/s) | |
|---|---|---|---|
| | | Before Grouting | After Grouting |
| 1 | RQSD | 970 | 2430 |
| 2 | RQSB | 1260 | 2260 |
| 3 | RQSDB | 810 | 2610 |
| 4 | RQSM | 850 | 2310 |
| 5 | RQPD | 1300 | 1870 |
| 6 | RQPB | 1430 | 1560 |
| 7 | RQPDB | 1190 | 1270 |
| 8 | RQPM | 910 | 1330 |

For smooth surface beam, before grouting on cracked beams RQSD pulse velocity on cracked portion has been observed 970 m/s which increase up to 2430 m/s after grouting. Before grouting on cracked beams RQSB pulse velocity on cracked portion has been observed 1260 m/s which increase up to 2260 m/s after grouting. Before grouting on cracked beams RQSDB pulse velocity on cracked portion has been observed 810 m/s which increase up to 2610 m/s after grouting. Before grouting on cracked beams RQSM pulse velocity on cracked portion has been observed 850 m/s which increase up to 2310 m/s after grouting.

For chipped surface beam, before grouting on cracked beams RQPD pulse velocity on cracked portion has been observed 1300 m/s which increase up to 1870 m/s after grouting. Before grouting on cracked beams RQPB pulse velocity on cracked portion has been observed 1430 m/s which increase up to 1560 m/s after grouting. Before grouting on cracked beams RQPDB pulse velocity on cracked portion has been observed 1190 m/s which increase up to 1270 m/s after grouting. Before grouting on cracked beams RQPM pulse velocity on cracked portion has been observed 910 m/s which increase up to 1330 m/s after grouting.

This suggest, after grouting pulse velocity of cracked beams increase for smooth surface and chipped surface beams, Which shows effectiveness of crack filling by grouting.

## 6.3 Failure Load Carrying Capacity

Load carrying capacity of repaired and strengthened beams is ranging from 250 kN to 310 kN. Experimental load carrying capacity for Strengthened beams is reported in Table 6.2

Table 6.2: Experimental load for repaired and strengthened beams

| Sr. No | Beams Notations | Experimental Failure Load(kN) |
|---|---|---|
| 1 | C1 | 60 |
| 2 | C2 | 55 |
| 3 | RQSD | 250 |
| 4 | RQSB | 270 |
| 5 | RQSDB | 290 |
| 6 | RQSM | 280 |
| 7 | RQPD | 290 |
| 8 | RQPB | 270 |
| 9 | RQPDB | 290 |
| 10 | RQPM | 310 |

Fig.6.1 shows comparison for load carrying capacity for repaired and strengthened beams.

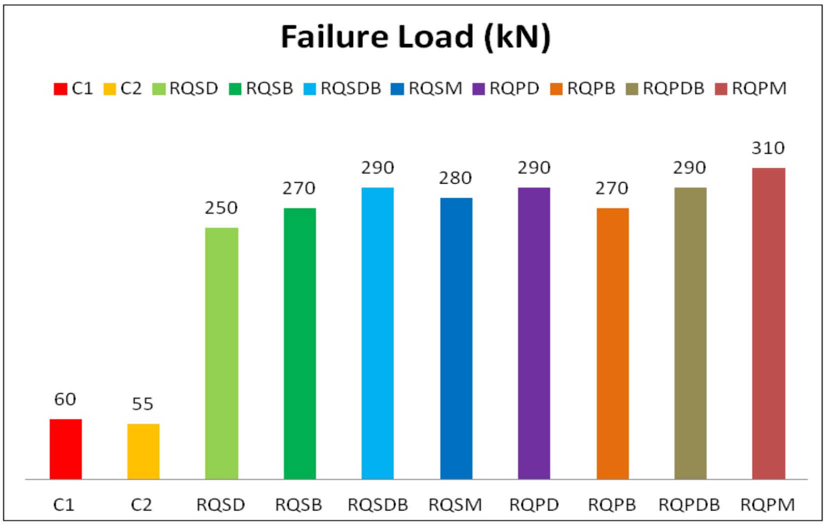



Figure 6.1: Failure Load for repaired and Strengthened Beams

Percentage increment in failure load is ranging from 334.78 % to 439.13 % for all repaired and strengthened beams as compared to that of control beams. This increment in failure load has been observed due to enlargement of cross section for jacketed beams as compared to that of control beam.Percentage increment in failure load is ranging from 3.7 % to 16 % for smooth surface repaired and strengthened beams. Percentage increment in failure load is ranging from 6.89 % to 14.81 % for chipped surface repaired and strengthened beams. Percentage increment in failure load for repaired and strengthened beams is presented in Table 6.3

Table 6.3: Percentage Increment in Failure Load for Repaired and Strengthened Beams

| Specimens | C | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
|---|---|---|---|---|---|---|---|---|---|
| C | 0 | 334.78 | 369.56 | 404.34 | 386.95 | 404.34 | 369.56 | 404.34 | 439.13 |
| RQSD | - | 0 | 8 | 16 | 12 | 16 | - | - | - |
| RQSB | - | -7.4 | 0 | 7.4 | 3.7 | - | 0 | - | - |
| RQSDB | - | -13.79 | -6.89 | 0 | -3.44 | - | - | 0 | - |
| RQSM | - | -10.71 | -3.57 | 3.57 | 0 | - | - | - | 10.71 |
| RQPD | - | -13.79 | - | - | - | 0 | -6.89 | 0 | 6.89 |
| RQPB | - | - | 0 | - | - | 7.4 | 0 | 7.4 | 14.81 |
| RQPDB | - | - | - | 0 | - | 0 | -6.89 | 0 | 6.89 |
| RQPM | - | - | - | - | -9.67 | -6.45 | -12.9 | -6.45 | 0 |

For smooth surface beams, failure load of 8 %, 16 % and 12 % has been observed for beams RQSB, RQSDB and RQSM as compared to that of beam RQSD. Failure load of -7.8 %, 7.4 % and 3.7 % has been observed for beams RQSD, RQSDB and RQSM as compared to that of beam RQSB. Failure load of -13.79 %, -6.89 % and -3.44 % has been observed for beams RQSD, RQSB and RQSM as compared to that of beam RQSDB. Failure load of -10.71 %, -3.57 % and 3.57 % has been observed for beams RQSD, RQSB and RQSDB as compared to that of beam RQSM.

For chipped surface beams, failure load of -6.89 % and 6.89 % has been observed for beams RQPB and RQPM as compared to that of beam RQPD. Failure load carrying capacity of beam RQPDB and beam RQPD has been observed at par. Failure load of 7.4 %, 7.4 % and 14.81 % has been observed for beams RQPD, RQPDB and RQPM as compared to that of beam RQPB. Failure load of -6.89 % and 6.89 % has been observed for beams RQPB and RQPM as compared to that of beam RQSDB. Failure load carrying capacity of beam RQPDB and beam RQPD has been observed at par. Failure load of -6.45 %, -12.9 % and -6.45 % has been observed for beams RQPD, RQPB and RQPDB as compared to that of beam RQPM.

Comparing performance of smooth surface and chipped surface beams, increment in failure load of beam 16 % has been observed for beam RQPD as compared to that for beam RQSD. Failure load carrying capacity of beam RQPB and beam RQSB has been observed at par. Failure load carrying capacity of beam RQPDB and beam RQSDB has been observed at par. Increment in failure load of 10.71 % has been observed for beam RQPM compared to that for beam RQSM.

For smooth surface beam higher load carrying capacity has been observed for beam RQSDB as compared to that for beam RQSD. This suggests that combined use of dowel connectors and bonding agent with micro-concrete is more effective techniques as compared to other techniques for beams with smooth surface.

For chipped surface beam higher load carrying capacity has been observed for beam RQPM as compared to that for beam RQPD. For chipped surface repaired and strengthened beams use of only micro-concrete without using dowel connectors and bonding agent is more effective jacketing techniques as compared to other techniques used.

## 6.4 Displacement

Displacement is measured at mid span and below point load at bottom side for the repaired and strengthened beams at interval of every 10 kN load till the failure of beams. Table 6.4 and 6.5 shows results of displacement for strengthened beams at mid span and below point load at bottom side, respectively.

Table 6.4: Results of Displacement for Repaired and Strengthened Beams at Mid Span

| Load | Beams Notations (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (kN) | C1 | C2 | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.33 | 0.82 | 0.17 | 0.09 | 0.15 | 0.15 | 0.12 | 0.12 | 0.06 | 0.09 |
| 20 | 1.11 | 1.4 | 0.38 | 0.24 | 0.27 | 0.35 | 0.33 | 0.33 | 0.16 | 0.28 |
| 30 | 2.19 | 2.6 | 0.58 | 0.41 | 0.48 | 0.59 | 0.61 | 0.57 | 0.38 | 0.48 |
| 40 | 3.69 | 3.78 | 0.84 | 0.64 | 1.37 | 0.85 | 0.83 | 0.85 | 0.53 | 0.67 |
| 50 | 4.99 | 5.2 | 1.02 | 0.81 | 0.85 | 0.97 | 0.98 | 1.2 | 0.72 | 0.78 |
| 60 | 12.28 | 11.85 | 1.37 | 1 | 1.06 | 1.15 | 1.09 | 1.33 | 0.9 | 0.92 |
| 70 | | | 1.53 | 1.16 | 1.2 | 1.39 | 1.28 | 1.47 | 1.14 | 1.11 |
| 80 | | | 1.69 | 1.57 | 1.5 | 1.54 | 1.38 | 1.72 | 1.36 | 1.3 |
| 90 | | | 2.15 | 1.75 | 1.79 | 1.59 | 1.58 | 2 | 1.5 | 1.51 |
| 100 | | | 2.31 | 2.2 | 2.23 | 2.05 | 1.81 | 2.25 | 1.78 | 1.69 |
| 110 | | | 2.48 | 2.5 | 2.54 | 2.25 | 2.01 | 2.5 | 1.96 | 1.93 |
| 120 | | | 3.45 | 2.69 | 2.93 | 2.45 | 2.18 | 2.77 | 2.19 | 2.13 |
| 130 | | | 4.01 | 3.47 | 3.34 | 2.66 | 2.38 | 2.93 | 2.35 | 2.33 |
| 140 | | | 5.7 | 3.99 | 3.5 | 2.9 | 2.62 | 3.1 | 2.55 | 2.61 |
| 150 | | | 5.4 | 4.3 | 3.72 | 3.15 | 2.83 | 3.35 | 2.73 | 2.9 |
| 160 | | | 6.15 | 4.57 | 5.27 | 3.31 | 3.03 | 3.65 | 3.03 | 3.1 |
| 170 | | | 7.53 | 4.8 | 6.77 | 3.52 | 3.24 | 3.85 | 3.28 | 3.3 |
| 180 | | | 8.95 | 5.3 | 8.04 | 3.7 | 3.48 | 4.08 | 3.43 | 3.56 |
| 190 | | | 10.4 | 5.67 | 11.4 | 3.96 | 3.63 | 4.25 | 3.63 | 3.8 |
| 200 | | | 11.02 | 6.55 | 12.37 | 4.14 | 3.83 | 4.45 | 3.83 | 4.11 |
| 210 | | | 11.51 | 9.05 | 14.66 | 4.42 | 4.08 | 4.65 | 4.07 | 4.38 |
| 220 | | | 12.55 | 10.75 | 16.69 | 4.62 | 4.28 | 4.95 | 4.23 | 4.66 |
| 230 | | | 13.81 | 12.2 | 17.7 | 4.88 | 4.48 | 5.3 | 4.43 | 4.86 |
| 240 | | | 14.4 | 15.9 | 20.47 | 5.3 | 4.73 | 5.75 | 5.9 | 5.08 |
| 250 | | | 16.55 | 18 | 21.76 | 6.25 | 5.14 | 8.6 | 7.23 | 5.29 |
| 260 | | | | 18.63 | 24.97 | 6.97 | 6.78 | 11.75 | 8.53 | 6.93 |
| 270 | | | | 24.13 | 26.36 | 9.7 | 7.48 | 13.25 | 11.83 | 8.68 |
| 280 | | | | | 29.54 | 14.7 | 11.03 | | 16.03 | 11.83 |
| 290 | | | | | 31.64 | | 15.08 | | 25.5 | 12.53 |
| 300 | | | | | | | | | | 24.23 |
| 310 | | | | | | | | | | 27.28 |

Table 6.5: Results of Displacement for Repaired and Strengthened Beams below Point Load

| Load | Beams Notations (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (kN) | C1 | C2 | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.29 | 0.66 | 0.13 | 0.09 | 0.1 | 0.09 | 0.11 | 0.11 | 0.04 | 0.12 |
| 20 | 0.89 | 1.21 | 0.27 | 0.21 | 0.16 | 0.25 | 0.28 | 0.31 | 0.14 | 0.24 |
| 30 | 0.61 | 2.41 | 0.42 | 0.36 | 0.25 | 0.41 | 0.5 | 0.52 | 0.32 | 0.39 |
| 40 | 2.89 | 3.63 | 0.63 | 0.51 | 0.33 | 0.6 | 0.7 | 0.74 | 0.46 | 0.59 |
| 50 | 4.11 | 5.35 | 0.8 | 0.66 | 0.42 | 0.71 | 0.8 | 1.04 | 0.62 | 0.68 |
| 60 | 5.66 | 7.43 | 0.98 | 0.81 | 0.58 | 0.84 | 0.92 | 1.17 | 0.78 | 0.89 |
| 70 | | | 1.2 | 0.94 | 0.72 | 1.02 | 1.07 | 1.29 | 0.97 | 1.04 |
| 80 | | | 1.33 | 1.28 | 0.95 | 1.15 | 1.15 | 1.49 | 1.06 | 1.2 |
| 90 | | | 1.73 | 1.46 | 1.29 | 1.39 | 1.35 | 1.74 | 1.29 | 1.37 |
| 100 | | | 1.88 | 1.83 | 1.58 | 1.55 | 1.54 | 1.97 | 1.51 | 1.55 |
| 110 | | | 2.05 | 2.08 | 1.85 | 1.71 | 1.71 | 2.21 | 1.64 | 1.73 |
| 120 | | | 2.95 | 2.25 | 2.19 | 1.87 | 1.85 | 2.47 | 1.84 | 1.9 |
| 130 | | | 3.45 | 2.98 | 2.52 | 2.08 | 2.03 | 2.09 | 1.98 | 2.09 |
| 140 | | | 4.1 | 3.41 | 2.69 | 2.29 | 2.23 | 2.77 | 2.14 | 2.35 |
| 150 | | | 4.65 | 3.66 | 2.93 | 2.5 | 2.41 | 3.02 | 2.32 | 2.61 |
| 160 | | | 5.33 | 3.9 | 3.27 | 2.63 | 2.58 | 3.27 | 2.57 | 2.78 |
| 170 | | | 6.8 | 4.11 | 4.43 | 2.82 | 2.75 | 3.47 | 2.73 | 2.96 |
| 180 | | | 8.15 | 4.51 | 6.47 | 2.95 | 2.91 | 3.72 | 2.92 | 3.19 |
| 190 | | | 9.47 | 5.59 | 8.53 | 3.2 | 3.1 | 3.87 | 3.08 | 3.41 |
| 200 | | | 9.95 | 6.36 | 9.36 | 3.36 | 3.3 | 4.02 | 3.27 | 3.68 |
| 210 | | | 10.5 | 7.58 | 11.29 | 3.64 | 3.53 | 4.24 | 3.45 | 3.94 |
| 220 | | | 11.45 | 9.36 | 12.72 | 3.8 | 3.7 | 4.54 | 3.63 | 4.24 |
| 230 | | | 12.85 | 10.79 | 13.57 | 4.05 | 3.9 | 4.87 | 3.82 | 4.49 |
| 240 | | | 13.5 | 14.28 | 15.62 | 5.45 | 4.13 | 5.22 | 4.82 | 4.93 |
| 250 | | | 15.65 | 16.24 | 16.48 | 6.39 | 4.5 | 7.12 | 5.72 | 5.98 |
| 260 | | | | 16.56 | 19.46 | 7.8 | 5.97 | 9.92 | 6.57 | 7.58 |
| 270 | | | | 20.59 | 20.59 | 9.9 | 7.8 | 12.32 | 9.82 | 9.13 |
| 280 | | | | | 23.97 | 11.8 | 9.95 | | 13.52 | 10.93 |
| 290 | | | | | 26.07 | | 13.3 | | 21.02 | 16.88 |
| 300 | | | | | | | | | | 20.88 |
| 310 | | | | | | | | | | 24.68 |

Load verses displacement relationship for strengthened beams at mid span and at point load below bottom side are presented in Fig. 6.2 and Fig. 6.3, respectively.

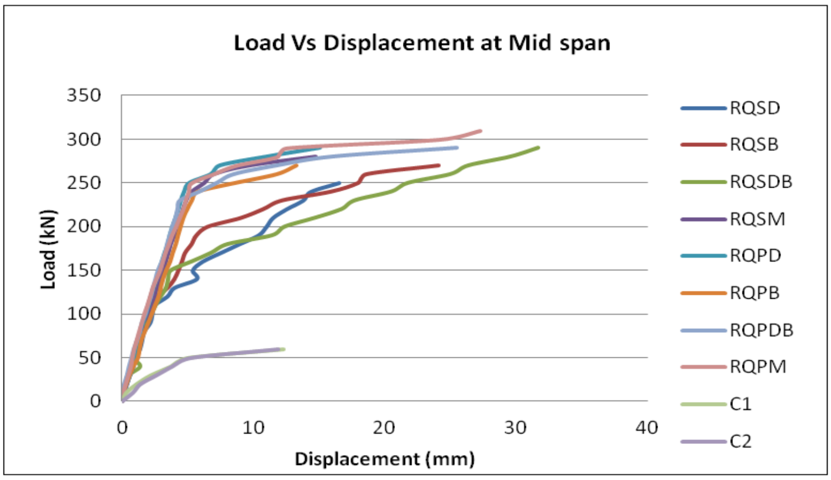



Figure 6.2: Load-Displacement relationship at Mid Span for Repaired and Strengthened Beams

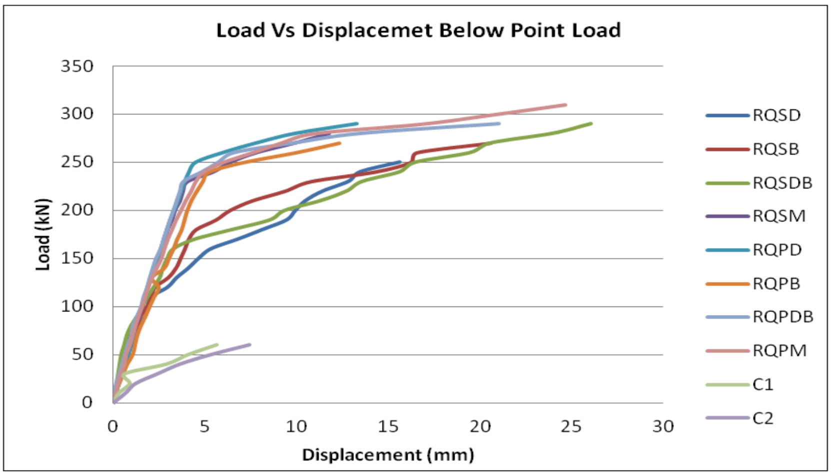



Figure 6.3: Load-Displacement relationship below Point Load for Repaired and Strengthened Beams

Percentage increment in displacement at mid span of repaired and strengthened beams is ranging from 9.82 % to 162.25 % as compared to that for control beam. Percentage increment in displacement below point load of repaired and strengthened beams is ranging from 80.29 % to 298.32 % as compare to that for control beam. This increment in displacement has been observed due to enlargement of cross section for jacketed beams as compared to that of control beam. Percentage increment in displacement at mid span is ranging from 12.58 % to 115.23 % for smooth surface repaired and strengthened beams. Percentage increment in displacement at mid span is ranging from 6.98 % to 105.88 % for chipped surface repaired and strengthened beams.

Percentage increment in displacement at mid span for repaired and strengthened beams is presented in table 6.6.

Table 6.6: Percentage Increment in Displacement at Mid Span for Repaired and Strengthened Beams

| Beams | C | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
|---|---|---|---|---|---|---|---|---|---|
| C | 0 | 37.17 | 100 | 162.24 | 21.84 | 24.98 | 9.82 | 111.35 | 126.1 |
| RQSD | - | 0 | 45.8 | 91.17 | -11.17 | -8.88 | - | - | - |
| RQSB | - | -31.41 | 0 | 31.12 | -39.07 | - | -45.08 | - | - |
| RQSDB | - | -47.69 | -23.73 | 0 | -53.53 | - | - | -19.4 | - |
| RQSM | - | 12.58 | 64.14 | 115.23 | 0 | - | - | - | 85.57 |
| RQPD | - | 9.74 | - | - | - | 0 | -12.13 | 69.09 | 80.9 |
| RQPB | - | - | 82.11 | - | - | 13.81 | 0 | 92.45 | 105.88 |
| RQPDB | - | - | - | 24.07 | - | -40.86 | -48.03 | 0 | 6.98 |
| RQPM | - | - | - | - | -46.11 | -44.72 | -51.42 | -6.52 | 0 |

For smooth surface beams, displacement at mid span of 45.8 %, 91.17 % and -11.17 % has been observed for beams RQSB, RQSDB and RQSM as compared to that of beam RQSD. Displacement at mid span of -47.69 %, -23.73 % and -53.33 % has been observed for beams RQSD, RQSB and RQSM as compared to that of beam RQSDB. Displacement at mid span of 12.58 %, 64.14 % and 115.23 % has been observed for beams RQSD, RQSB and RQSDB as compared to that of beam RQSM.

For chipped surface beams, displacement at mid span of -12.13 %, 69.09 % and 80.9 % has been observed for beams RQPB, RQPDB and RQPM as compared to that of beam RQPD. Displacement at mid span of 13.81 %, 92.45 % and 105.88 % has been observed for beams RQPD, RQPDB and RQPM as compared to that of beam RQPB. Displacement at mid span of -40.86 %, -48.03 % and 6.98 % has been observed for beams RQPD, RQPB and RQPM as compared to that of beam RQSDB. Displacement at mid span of -44.72 %, -51.42 % and -6.52 % has been observed for beams RQSD, RQPB and RQPDB as compared to that of beam RQPM.

Comparing performance of smooth surface and chipped surface beams, reduction in displacement at mid span of beam -8.88 % has been observed for beam RQPD as compared to that for beam RQSD. Decrement in displacement at mid span of -45.08 % has been observed for beam RQPB compared to that for beam RQSB. Decrement in displacement at mid span of -19.4 % has been observed for beam RQPDB as compared to that for beam RQSDB. Increment in displacement at mid span of 85.57 % has been observed for beam RQPM compared to that for beam RQSM.

For smooth surface beam, at higher load higher displacement of beam RQSDB has been observed as compared to that for beam RQSD. This suggests that combined use of dowel connectors and bonding agent with micro-concrete is more effective techniques as compared to other techniques for beams with smooth surface.

For chipped surface beam, at higher load higher displacement of beam RQPM has been observed as compared to that for beam RQSD. This suggest that for chipped surface strengthened beams use of only micro-concrete without using dowel connectors and bonding agent is more effective jacketing techniques as compared to other techniques used.

## 6.5 Strain

Strain is evaluated at four different positions for repaired and strengthened beams as same as discussed in chapter 5 in section 5.4 Position-1 indicates strain in concrete evaluated at location above 60 mm from bottom surface of the beam. Results are presented in table 6.7 for the repaired and strengthened beams. Position-2 indicates results of strain in concrete measured at 20 mm above from bottom surface. Corresponding results of strain are presented in table6.8 Position-3 indicates results of strain in concrete at mid span at bottom surface for the repaired and strengthened beams. The results of strain are presented in table6.9 Position-4 indicates strain in concrete under point load on bottom surface in for the beams. The corresponding results are given in table 6.10.

Table 6.7: Strain at Position-1 for Repaired and Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.00001 | 0 | -0.00094 | -0.00001 | -0.00003 | -0.00001 | 0.00004 | 0.00004 |
| 20 | 0.00001 | 0 | -0.0013 | -0.00001 | -0.00003 | -0.00001 | 0.00011 | 0.00012 |
| 30 | 0.00002 | 0 | -0.00148 | -0.00001 | -0.00004 | -0.00001 | 0.00007 | 0.00017 |
| 40 | 0.00001 | 0 | -0.00175 | -0.00001 | -0.00003 | -0.00001 | 0.00005 | 0.00026 |
| 50 | -0.00001 | 0 | -0.00199 | -0.00001 | -0.00004 | -0.00002 | 0.00011 | 0.00025 |
| 60 | -0.00003 | 0 | -0.00223 | -0.00002 | -0.00004 | -0.00002 | 0.00014 | 0.00029 |
| 70 | -0.00002 | 0 | -0.00248 | -0.00002 | -0.00004 | -0.00001 | 0.0001 | 0.00038 |
| 80 | -0.00003 | 0.00001 | -0.00271 | -0.00002 | -0.00004 | -0.00002 | 0.01655 | 0.00049 |
| 90 | -0.00005 | 0 | -0.00279 | -0.00002 | -0.00004 | -0.00001 | 0.01609 | 0.0009 |
| 100 | -0.00005 | 0.00001 | -0.0028 | -0.00003 | -0.00004 | -0.00001 | 0.01853 | 0.00123 |
| 110 | -0.00005 | 0.00001 | -0.0029 | -0.00005 | -0.00003 | -0.00001 | 0.02141 | 0.00165 |
| 120 | 0.00006 | 0.00001 | -0.00296 | -0.00004 | -0.00003 | -0.00001 | 0.02372 | 0.00211 |
| 130 | 0.00002 | 0.00001 | -0.00313 | -0.00005 | -0.00003 | -0.00001 | 0.02421 | 0.00224 |
| 140 | 0.00002 | 0.00001 | -0.00328 | -0.00008 | -0.00003 | 0 | 0.02667 | 0.00233 |
| 150 | 0.00001 | 0 | -0.00336 | -0.00008 | -0.00003 | -0.00001 | 0.02679 | 0.00277 |
| 160 | 0.00002 | 0 | -0.00357 | -0.00008 | -0.00003 | -0.00001 | 0.02913 | 0.00311 |
| 170 | 0.00003 | -0.00001 | -0.00424 | -0.00008 | -0.00003 | 0 | 0.01342 | 0.00333 |
| 180 | 0.00002 | -0.00001 | -0.00428 | -0.00008 | -0.00007 | -0.00002 | 0.01407 | 0.00352 |
| 190 | 0.00003 | -0.00002 | -0.00427 | -0.00008 | -0.00007 | -0.00001 | 0.01269 | 0.00364 |
| 200 | 0.00004 | -0.00002 | -0.00426 | -0.00008 | -0.00007 | -0.00001 | 0.01221 | 0.00377 |
| 210 | 0.00017 | -0.00002 | -0.00423 | -0.00008 | -0.00007 | -0.00001 | 0.01057 | 0.00401 |
| 220 | 0.00045 | -0.00002 | -0.00412 | -0.00009 | -0.00006 | -0.00001 | 0.00628 | 0.0041 |
| 230 | 0.00059 | -0.00002 | -0.00409 | -0.00009 | -0.00006 | 0 | 0.0062 | 0.00421 |
| 240 | 0.0006 | -0.00002 | -0.004 | -0.00009 | -0.00006 | 0.00003 | 0.00595 | 0.00421 |
| 250 | 0.00078 | -0.00002 | -0.00394 | -0.0001 | -0.00005 | 0.0007 | | 0.00453 |
| 260 | | -0.00001 | -0.00386 | -0.0001 | 0.00066 | 0.00127 | | 0.00463 |
| 270 | | -0.00001 | -0.00379 | -0.00009 | 0.00084 | 0.00148 | | 0.00054 |
| 280 | | | -0.00362 | -0.00009 | 0.00088 | | | -0.00055 |
| 290 | | | -0.00342 | | 0.00004 | | | |

Table 6.8: Strain at Position-2 for Repaired and Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00001 |
| 10 | -0.00001 | -0.00049 | 0 | -0.00007 | -0.00004 | -0.00002 | 0.00005 | -0.00048 |
| 20 | -0.00002 | -0.0006 | 0.00001 | -0.00008 | -0.00004 | -0.00002 | 0.00002 | -0.00059 |
| 30 | -0.00002 | -0.00175 | 0.00001 | -0.00012 | -0.00004 | -0.00003 | 0.00007 | -0.00174 |
| 40 | -0.00002 | -0.00209 | 0.00001 | -0.00019 | -0.00005 | -0.00003 | 0.00015 | -0.00208 |
| 50 | -0.00002 | -0.00157 | 0.00001 | -0.00025 | -0.00005 | -0.00003 | 0.00017 | -0.00156 |
| 60 | -0.00003 | -0.00149 | 0.00002 | -0.00033 | -0.00006 | -0.00003 | 0.00025 | -0.00148 |
| 70 | -0.00003 | -0.00188 | 0.00002 | -0.00039 | -0.00008 | -0.00003 | 0.00026 | -0.00187 |
| 80 | -0.00003 | -0.00102 | 0.00001 | -0.00042 | -0.00009 | -0.00003 | -0.00087 | -0.00101 |
| 90 | -0.00003 | -0.00112 | -0.00002 | -0.00045 | -0.00011 | -0.00003 | -0.00094 | -0.00111 |
| 100 | -0.00003 | -0.00331 | -0.00001 | -0.00055 | -0.00011 | -0.00003 | -0.00103 | -0.0033 |
| 110 | -0.00003 | -0.00377 | -0.00002 | -0.0013 | -0.00016 | -0.00002 | -0.00108 | -0.00376 |
| 120 | -0.00003 | -0.01017 | -0.00002 | -0.00147 | -0.00018 | -0.00002 | -0.00114 | -0.01016 |
| 130 | -0.00005 | -0.01329 | -0.00002 | -0.00151 | -0.0002 | -0.00003 | -0.00095 | -0.01328 |
| 140 | -0.00006 | -0.01347 | -0.00002 | -0.0023 | -0.0002 | -0.00002 | -0.00038 | -0.01346 |
| 150 | -0.00006 | 0.00119 | -0.00002 | -0.00228 | -0.00011 | -0.00002 | -0.00005 | 0.0012 |
| 160 | -0.00006 | -0.00294 | -0.00002 | -0.00259 | -0.00012 | -0.00001 | -0.00007 | -0.00293 |
| 170 | -0.00007 | -0.00454 | -0.00003 | -0.00251 | -0.00009 | -0.00002 | -0.00025 | -0.00453 |
| 180 | -0.00007 | -0.00061 | -0.00003 | -0.00253 | -0.00015 | -0.00003 | -0.00027 | -0.0006 |
| 190 | -0.00007 | -0.00072 | -0.00005 | -0.00261 | -0.00012 | -0.00002 | -0.00058 | -0.00071 |
| 200 | -0.00007 | -0.0008 | -0.00006 | -0.00308 | -0.0001 | -0.00002 | -0.00076 | -0.00079 |
| 210 | -0.00006 | 0.00065 | -0.00007 | -0.00288 | -0.00011 | -0.00002 | -0.00086 | 0.00066 |
| 220 | -0.00004 | 0.00019 | -0.00006 | -0.00373 | -0.0001 | -0.00001 | -0.0009 | 0.0002 |
| 230 | 0.00004 | 0.00098 | -0.00006 | -0.0023 | -0.00013 | 0.00001 | -0.00094 | 0.00099 |
| 240 | 0.00005 | -0.00036 | -0.00012 | -0.00254 | -0.00019 | 0.00009 | -0.00101 | -0.00035 |
| 250 | 0.00052 | -0.03134 | -0.00017 | -0.00374 | -0.00008 | 0.00089 | -0.0009 | -0.03133 |
| 260 | | -0.00714 | -0.00009 | -0.0043 | 0.00012 | 0.00102 | -0.0009 | -0.00713 |
| 270 | | -0.01397 | -0.00006 | -0.0011 | -0.00009 | 0.00098 | -0.00104 | -0.01396 |
| 280 | | | 0 | -0.00065 | -0.00295 | | -0.00101 | 0.00001 |
| 290 | | | -0.00003 | | -0.00295 | | -0.00105 | 0.00001 |
| 300 | | | | | | | | 0.00001 |
| 310 | | | | | | | | 0.00001 |

Table 6.9: Strain at Position-3 for Repaired and Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | -0.00004 | -0.00002 | -0.00001 | -0.00002 | -0.00004 | 0.00006 | 0.00031 |
| 20 | 0 | -0.00008 | -0.00003 | -0.00002 | -0.00001 | -0.00005 | 0.00005 | 0.00017 |
| 30 | 0 | -0.00012 | -0.00004 | -0.00002 | -0.00001 | -0.00006 | 0.00014 | 0.00028 |
| 40 | 0 | -0.00028 | -0.00005 | -0.00001 | -0.00001 | -0.00006 | 0.00026 | 0.00007 |
| 50 | 0 | -0.00034 | -0.00006 | -0.00002 | -0.00002 | -0.00008 | 0.00031 | 0.00022 |
| 60 | -0.00001 | -0.00036 | -0.00005 | -0.00003 | -0.00003 | -0.00008 | 0.00051 | -0.00021 |
| 70 | -0.00001 | -0.00041 | -0.00006 | -0.00003 | -0.00004 | -0.00008 | 0.00127 | 0.0002 |
| 80 | -0.00001 | -0.00045 | -0.00007 | -0.00003 | -0.00005 | -0.00008 | -0.00024 | 0.0002 |
| 90 | -0.00001 | -0.00045 | 0.00003 | -0.00004 | -0.00006 | -0.00006 | -0.00025 | 0.00018 |
| 100 | -0.00001 | -0.00046 | 0.00003 | -0.00004 | -0.00008 | -0.00005 | -0.00023 | 0.0002 |
| 110 | -0.00001 | -0.0005 | 0.00004 | -0.00005 | -0.00009 | -0.00004 | -0.00019 | 0.00007 |
| 120 | -0.00001 | -0.00053 | 0.00005 | -0.00005 | -0.00009 | -0.00003 | -0.00026 | 0.00013 |
| 130 | 0 | -0.00057 | 0.00006 | -0.00006 | -0.0001 | -0.00003 | -0.00027 | 0.00013 |
| 140 | -0.00001 | -0.00056 | 0.00007 | -0.00007 | -0.0001 | 0 | -0.00027 | 0.00022 |
| 150 | -0.00001 | -0.00067 | 0.00007 | -0.00007 | -0.00011 | 0.00002 | -0.00028 | 0.0002 |
| 160 | -0.00001 | -0.00067 | 0.00009 | -0.00008 | -0.00012 | 0.00003 | -0.00025 | 0.00016 |
| 170 | -0.00001 | -0.00068 | 0.00004 | -0.00007 | -0.00012 | 0.00001 | -0.00032 | 0.00016 |
| 180 | -0.00001 | -0.00072 | 0.00008 | -0.00008 | -0.00014 | 0.00003 | -0.00023 | 0.00015 |
| 190 | -0.00002 | -0.00073 | 0.00007 | -0.00008 | -0.00014 | 0.00004 | -0.00024 | 0.00012 |
| 200 | -0.00001 | -0.00072 | 0.00009 | -0.00008 | -0.00015 | 0.00006 | -0.00032 | 0.00011 |
| 210 | -0.00005 | -0.00074 | -0.00002 | -0.00008 | -0.00015 | 0.00015 | -0.00029 | 0.00013 |
| 220 | 0.00003 | -0.0008 | -0.00009 | -0.00008 | -0.00015 | 0.00024 | -0.00029 | 0.00016 |
| 230 | 0.00001 | -0.00078 | -0.00007 | -0.00008 | -0.00016 | 0.00055 | -0.00027 | 0.00016 |
| 240 | 0.00001 | -0.00086 | -0.00007 | -0.00008 | -0.00016 | 0.0017 | -0.0003 | 0.00013 |
| 250 | 0 | -0.00087 | -0.00006 | -0.00009 | -0.00017 | 0.00238 | -0.00032 | 0.00015 |
| 260 | | -0.00085 | -0.00018 | -0.00009 | -0.00016 | 0.00289 | -0.0003 | 0.00034 |
| 270 | | -0.00043 | -0.00018 | 0.00014 | -0.00016 | 0.00467 | -0.00071 | 0.00049 |
| 280 | | | -0.00018 | 0.00011 | -0.00016 | | -0.00056 | 0.00033 |
| 290 | | | -0.00018 | | -0.00005 | | -0.00047 | 0.00065 |
| 300 | | | | | | | | 0.0008 |
| 310 | | | | | | | | 0.00088 |

Table 6.10: Strain at Position-4 for Repaired and Strengthened Beams

| Load | Beams Notations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (kN) | RQSD | RQSB | RQSDB | RQSM | RQPD | RQPB | RQPDB | RQPM |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | -0.00001 | -0.00001 | -0.00001 | 0 | -0.00002 | -0.00002 | -0.00008 | 0.00005 |
| 20 | -0.00001 | -0.00001 | -0.00002 | -0.00001 | -0.00002 | -0.00003 | -0.00005 | 0.00004 |
| 30 | -0.00001 | -0.00001 | -0.00001 | -0.00001 | -0.00003 | -0.00003 | -0.00002 | -0.00005 |
| 40 | -0.00001 | -0.00002 | 0 | -0.00001 | -0.00003 | -0.00003 | -0.00006 | 0.00003 |
| 50 | -0.00002 | -0.00001 | -0.00002 | -0.00001 | -0.00003 | -0.00003 | -0.00008 | 0.00003 |
| 60 | -0.00003 | -0.00001 | -0.00002 | -0.00002 | -0.00003 | -0.00003 | -0.00011 | -0.00006 |
| 70 | -0.00004 | -0.00001 | -0.00004 | -0.00002 | -0.00003 | -0.00004 | -0.00011 | 0.00007 |
| 80 | -0.00005 | -0.00002 | -0.00005 | -0.00002 | -0.00003 | -0.00004 | -0.00015 | -0.00009 |
| 90 | -0.00009 | -0.00002 | -0.00006 | -0.00002 | -0.00003 | -0.00004 | -0.00011 | -0.00011 |
| 100 | -0.0001 | -0.00001 | -0.00005 | -0.00002 | -0.00003 | -0.00005 | -0.00011 | -0.00023 |
| 110 | -0.00011 | -0.00001 | -0.00006 | -0.00005 | -0.00003 | -0.00005 | -0.00015 | -0.00013 |
| 120 | -0.00012 | -0.00002 | -0.00006 | -0.00005 | -0.00003 | -0.00005 | -0.00014 | -0.00003 |
| 130 | -0.00016 | -0.00002 | -0.00007 | 0.00013 | -0.00004 | -0.00005 | -0.00012 | 0.00016 |
| 140 | -0.00017 | -0.00002 | -0.00008 | 0.00006 | -0.00004 | -0.00005 | -0.0001 | -0.00015 |
| 150 | -0.00017 | -0.00003 | -0.00008 | 0.00009 | -0.00004 | -0.00006 | -0.00015 | -0.00006 |
| 160 | -0.00018 | -0.00003 | -0.00008 | 0.00011 | -0.00005 | -0.00005 | -0.00013 | -0.00012 |
| 170 | -0.00017 | -0.00003 | -0.0001 | 0.00013 | -0.00005 | -0.00006 | -0.00006 | 0.00001 |
| 180 | -0.00008 | -0.00003 | -0.0001 | 0.00015 | -0.00008 | -0.00006 | -0.00001 | -0.00005 |
| 190 | 0.00007 | -0.00004 | -0.00012 | 0.00017 | -0.00008 | -0.00006 | -0.00001 | 0 |
| 200 | 0.00038 | -0.00004 | -0.0001 | 0.00018 | -0.00009 | -0.00006 | 0.00002 | -0.00003 |
| 210 | 0.00017 | -0.00004 | -0.0001 | 0.0002 | -0.00009 | -0.00007 | 0.00008 | 0.00012 |
| 220 | 0.00033 | -0.00004 | -0.00011 | 0.00021 | -0.00009 | -0.00007 | 0.00008 | 0.00005 |
| 230 | 0.00041 | -0.00004 | -0.00011 | 0.00021 | -0.00009 | -0.00007 | 0.00009 | -0.00029 |
| 240 | 0.00064 | -0.00004 | -0.00012 | 0.00034 | -0.00009 | -0.00007 | 0.00005 | -0.00014 |
| 250 | 0.00013 | -0.00004 | -0.00009 | 0.00087 | -0.00009 | -0.00007 | -0.00007 | 0.00011 |
| 260 | | -0.00004 | -0.00008 | 0.00048 | -0.0001 | -0.00008 | -0.00009 | -0.00013 |
| 270 | | -0.00004 | -0.00009 | 0.00041 | -0.0001 | -0.00008 | -0.00011 | -0.00003 |
| 280 | | | -0.00009 | 0.00026 | -0.0001 | | -0.00019 | 0 |
| 290 | | | -0.0001 | | -0.00011 | | 0.00002 | -0.00011 |
| 300 | | | | | | | | 0.00005 |
| 310 | | | | | | | | -0.00017 |

Fig. 6.4 show load vs strain variation in concrete evaluated at positon-1 for repired and strengthened RC beams.

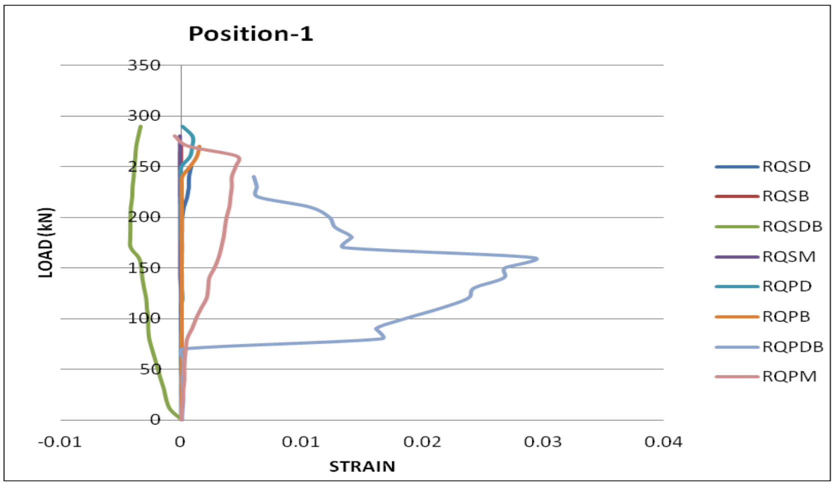



Figure 6.4: Load vs Strain Variation in Concrete evaluated at Positon-1 for Repaired and Strengthened RC Beams

Fig. 6.5 show load vs strain variation in concrete evaluated at positon-2 for repaired and strengthened RC beams.

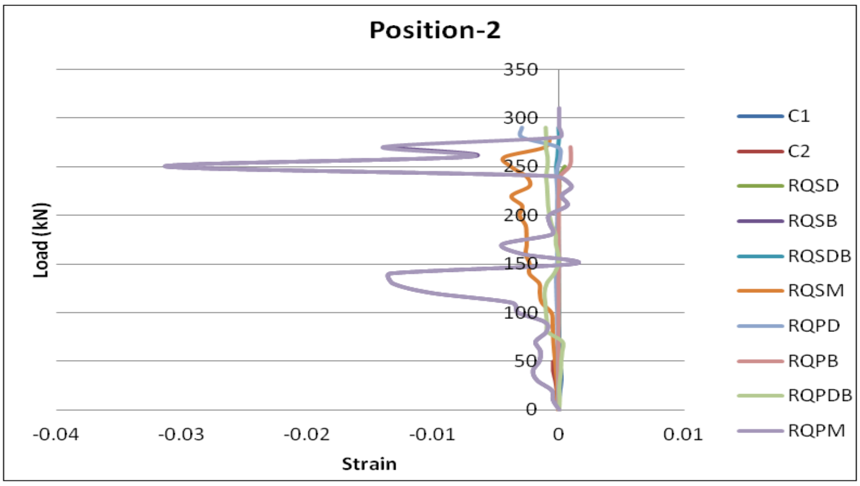



Figure 6.5: show load vs strain variation in concrete evaluated at positon-2 for repaired and strengthened RC beams.

Fig. 6.6 show load vs strain variation in concrete evaluated at positon-3 for repaired and strengthened RC beams.

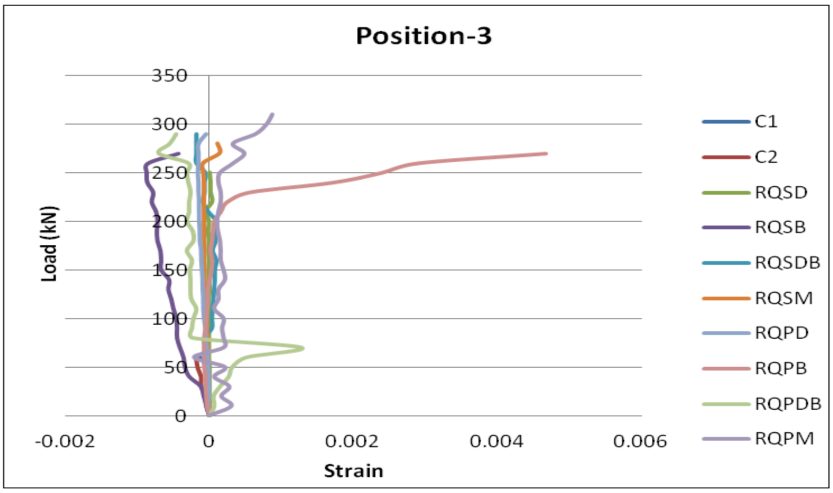



Figure 6.6: Load vs Strain Variation in Concrete evaluated at Positon-3 for Repaired and Strengthened RC Beams

Fig.6.7 show load vs strain variation in concrete evaluated at positon-4 for repaired and strengthened RC beams.

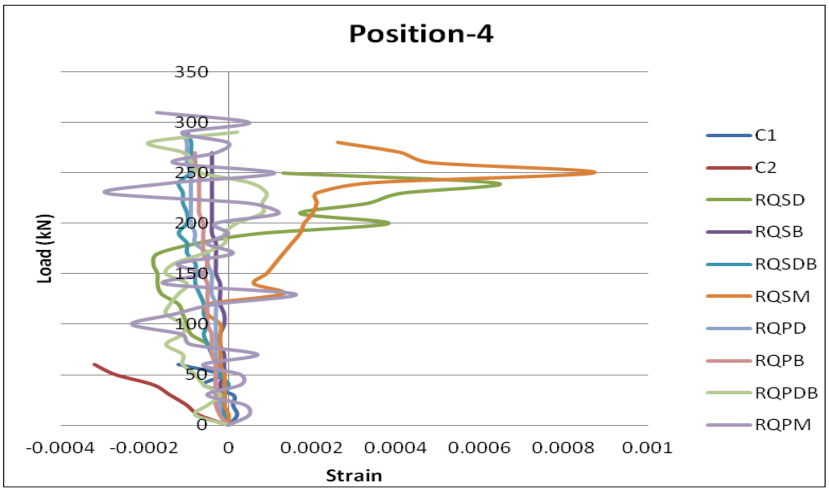



Figure 6.7: Load vs Strain Variation in Concrete evaluated at Positon-4 for Repaired and Strengthened RC Beams

Maximum Strain has been observed for beams RQSDB, RQPDB and RQPM as compared to that for RQSD for all the positions. Higher strain is observed due to good bonding between new concrete to old concrete. Good bonding has been observed due to effectiveness of combined use of dowel connectors and bonding agent for the smooth surface beams. For chipped surface beam only micro-concrete is observed more effective as compared to that for dowel connectors and bonding agent, respectively.

## 6.6 Failure Mode and Crake Pattern

Initial cracks are observed between 120 kN to 180 kN load for repaired and strengthened beams. Cracks are observed in pure bending portion for the beam. Maximum sizes of cracks on majority occasions are seen in middle third portion and on the cracks which were grouted before jacketing. Small cracks also were observed near all big cracks. For the beams continuous cracks are observed on bottom face of the beam. At the time of failure cracks are observed up to top bonding plane of old to new concrete for the beams. Maximum crack widths in range of 8mm to 10mm have been observed for beams RQSDB and RQPM at the failure load.Fig. 6.8 (a) and Fig.6.8 (b) show crack pattern and failure mode of control beam, respectively.

(a) Crack Pattern for control Beam (b) Failure Mode for control Beam

Figure 6.8: Crack pattern and failure mode of control beam

Fig. 6.9 (a) and Fig. 6.9 (b) show crack pattern and failure mode of beam QSD, respectively.

(a) Crack Pattern for Beam RQSD (b) Failure Mode for Beam RQSD

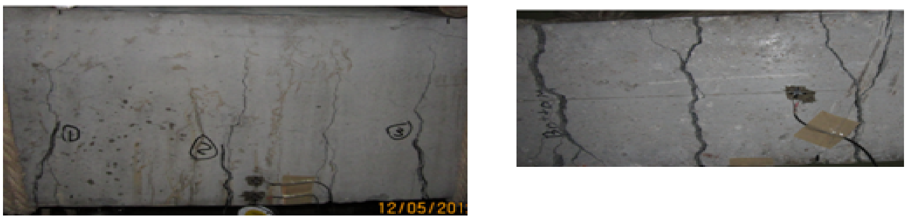
Figure 6.9: Crack pattern and Failure mode of beam RQSD

Fig. 6.10 (a) and Fig. 6.10 (b) show crack pattern and failure mode of beam RQSB, respectively.

(a) Crack Pattern for Beam RQSB (b) Failure Mode for Beam RQSB

Figure 6.10: Crack pattern and Failure mode of beam RQSB

Fig.6.11 (a) and Fig. 6.11 (b) show crack pattern and failure mode of beam RQSDB, respectively.




(a) Crack Pattern for Beam RQSDB (b) Failure Mode for Beam RQSDB

Figure 6.11: Crack pattern and Failure mode of beam RQSDB

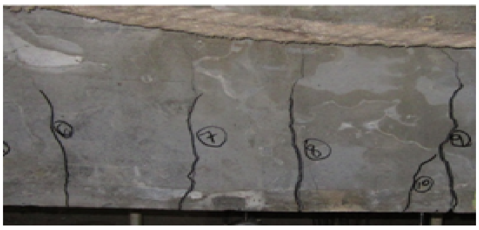
Fig. 6.12 (a) and Fig. 6.12 (b) show crack pattern and failure mode of beam RQSM, respectively.

(a) Crack Pattern for Beam RQSM


(b) Failure Mode for Beam RQSM

Figure 6.12: Crack pattern and Failure mode of beam RQSM

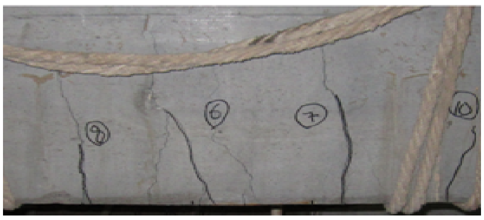
Fig. 6.13 (a) and Fig. 6.13 (b) show crack pattern and failure mode of beam RQPD, respectively.


(a) Crack Pattern for Beam RQPD


(b) Failure Mode for Beam RQPD

Figure 6.13: Crack pattern and Failure mode of beam RQPD

Fig. 6.14 (a) and Fig. 6.14 (b) show crack pattern and failure mode of beam RQCB, respectively.


(a) Crack Pattern for Beam RQPB


(b) Failure Mode for Beam RQPB

Figure 6.14: Crack pattern and Failure mode of beam RQPB

Fig. 6.15 (a) and Fig. 6.15 (b) show crack pattern and failure mode of beam RQPDB, respectively.

(a) Crack Pattern for Beam RQPDB (b) Failure Mode for Beam RQPDB

Figure 6.15: Crack pattern and Failure mode of beam RQPDB

Fig. 6.16 (a) and Fig. 6.16 (b) show crack pattern and failure mode of beam RQPM, respectively.

(a) Crack Pattern for Beam RQPM (b) Failure Mode for Beam RQPM

Figure 6.16: Crack pattern and Failure mode of beam RQPM

## 6.7 Comparison with Analytical Results

Experimental and analytical results for load carrying capacity for repaired and strengthened beams are compared in table 6.11.

Table 6.11: Experimental and Analytical Results for Load for strengthened Beams

| Sr. No | Beams Notations | Experimental Failure Load (kN) | Analytical Failure Load |
|---|---|---|---|
| 1 | C1 | 60 | 49.59 |
| 2 | C2 | 55 | 49.59 |
| 3 | RQSD | 250 | 165.04 |
| 4 | RQSB | 270 | 165.55 |
| 5 | RQSDB | 290 | 165.25 |
| 6 | RQSM | 280 | 165.44 |
| 7 | RQPD | 290 | 165.16 |
| 8 | RQPB | 270 | 165.22 |
| 9 | RQPDB | 290 | 165.16 |
| 10 | RQPM | 310 | 164.91 |

For control beam increment of experimental load of 21% and 10.91% has been observed as compared to that for analytical load. For smooth surface beams, increment of experimental load of 51.48% has been observed for beam RQSD as compared to that of analytical load. Increment of experimental load of 63.09% has been observed for beam RQSB as compared to that of analytical load. Increment of experimental load of 75.49% has been observed for beam RQSDB as compared to that of analytical load. Increment of experimental load of 69.25% has been observed for beam RQSM as compared to that of analytical load.

For chipped surface beams, increment of experimental load of 75.59% has been observed for beam RQPD as compared to that of analytical load. Increment of experimental load of 63.42% has been observed for beam RQPB as compared to that of analytical load. Increment of experimental load of 75.59% has been observed for beam RQPDB as compared to that of analytical load. Increment of experimental load of 87.98% has been observed for beam RQPM as compared to that of analytical load.

For beams with smooth surface, highest failure load of 290 kN is observed for beam RQSDB due to combined use of dowel connectors and bonding agent with micro-concrete as compared to that for other jacketing techniques.

For beams with chipped surface, highest failure load of 310 kN is observed for beam RQPM due only micro-concrete without dowel connectors and bonding agent as compared to that for other jacketing techniques.

## 6.8 Strengthened Beams Vs Repaired and Strengthened Beams

Maximum failure load from all smooth surface strengthened beams and repaired and strengthened beams have been observed for beam QSDB and RQSDB. From load vs displacement relationship, higher displacement at higher load has been observed for beam QSDB and RQSDB from all strengthened and repaired and strengthened beams. From this study it has been observed that jacketing techniques of combined use of dowel connectors and bonding agent is more suitable for smooth surface beam.

Maximum failure load from all chipped surface strengthened beams and repaired and strengthened beams have been observed for beam QPM and RQPM. From load vs displacement relationship, higher displacement at higher load has been observed for beam RQPM and RQPM from all strengthened and repaired and strengthened beams. From this study it has been observed that for chipped surface beam there is no requirement of such jacketing techniques, only use of micro-concrete is more effective. This beneficial effect was found due to good bonding of old to new concrete in both cases.

For beam with smooth surface and dowel connectors good bond around dowel connectors is found and portion apart from it, no bonding was found is clearly shown in Fig. 6.17.

Figure 6.17: Beam with Smooth Surface and Dowel Connectors

For beam with smooth surface and bonding agent partial bonding was observed is shown in Fig. 6.18


Figure 6.18: Beam with Smooth Surface and Bonding Agent

From Fig. 6.19, it was observed that for smooth surface beam without use of dowel connectors and bonding agent show poor bond.

Figure 6.19: Beam with Smooth Surface and without combined Dowel connectors and Bonding Agent

From Fig. 6.20, it has been observed that beam with chipped surface and dowel connectors shows good bonding shown below.

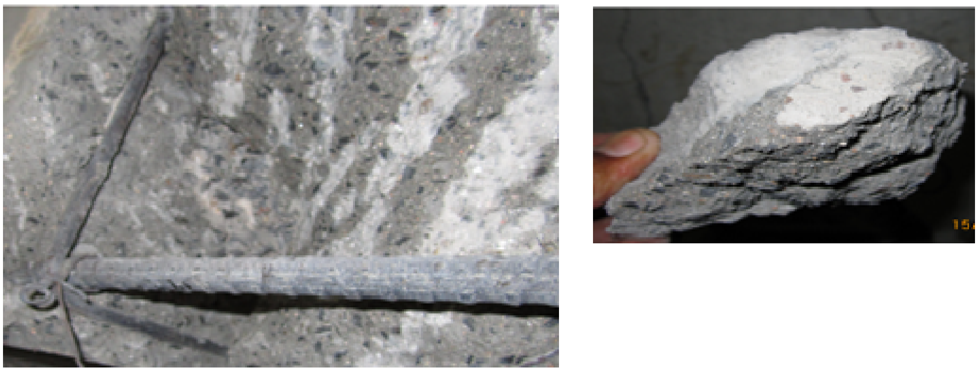


Figure 6.20: Beam with Chipped Surface and Dowel Connectors

From Fig. 6.21, it was noted that for beam with chipped surface and combined use of dowel connectors and bonding agent show good bonding.


Figure 6.21: Beam with Chipped Surface and combined Dowel connectors and Bonding Agent

For beam with chipped surface and without dowel connector and bonding agent show good bond between old to new concrete is shown in Fig. 6.22.

Figure 6.22: Beam with Chipped Surface and without combined Dowel connectors and Bonding Agent

# Chapter 7

# Concluding Remarks and Future Scope

## 7.1 Summary

For understanding basic requirement of strengthening by jacketing, different techniques, properties of material, behaviour of RC beams after jacketing literature has been studied. Total 28 day of curing period is given to strengthened beams and repaired and strengthened beam. Total eighteen beams are tested. Out of that eight beams are strengthened. Other eight are tested, repaired by grouting, strengthened and retested. Two beams are tested as control beams. For damaged beams grouting has been done for cack filling before jacketing. For checking effectiveness of grouting for filling up of cracks, Ultrasonic pulse velocity test is conducted on all grouted beams. Design of control beams and jacketed beams is made using codal provisions of IS-456[8]. All strengthened and repaired and strengthened beams are designed as under-reinforced beams, respectively. Testing of beams is done under two point loading system. The beams are strengthened using different jacketing techniques. Jacketing techniques like use of dowel connectors and micro-concrete, bonding agent and micro-concrete, combined use of dowel connectors, bonding agent and micro-concrete and using only micro-concrete without dowel connectors and bonding agent. Repairing and Strengthening is carried out on chipped and smooth surface beams. Different parameters like failure load, displacement, strain in concrete at different positions, failure modes, crack patterns etc. are evaluated for beams. Variation evaluated in failure load and displacement capacity of beams is carefully observed. Experimental test results are compared with values calculated from codal provisions as per IS-456. Also bond strength of smooth surface and chipped surface beams is evaluated during testing.

## 7.2 Concluding Remarks

Following concluding remarks have been made on basis of the work conducted:

**(a) Strengthened Beams**

- The experimental results clearly demonstrate that jacketing of the beam can enhance structural properties.

- For smooth surface strengthened beams, highest load carrying capacity has been observed for beam using combined dowel connectors and bonding agent with micro-concrete as compared to other beams.

- For smooth surface strengthened beams, higher displacement at higher load has been observed for beam using combined dowel connectors and bonding agent with micro-concrete as compared to other beams.

- For smooth surface strengthened beams, higher strain has been observed at higher load for beam using combined dowel connectors and bonding agent with micro-concrete as compared to other beams.

- For smooth surface beams strengthened by jacketing, combined use of dowel connectors and bonding agent with micro-concrete gives good bond between old to new concrete.

- For chipped surface strengthened beams, highest load carrying capacity has been observed for beam with only micro-concrete and without dowel connectors and bonding agent as compared to other beams.

- For chipped surface strengthened beams, higher displacement at higher load has been observed for beam with only micro-concrete and without dowel connectors and bonding agent as compared to other beams.

- For chipped surface strengthened beams, higher strain at higher load has been observed for beam with only micro-concrete and without dowel connectors and bonding agent as compared to other beams.

- Use only micro-concrete for chipped surface jacketed beam without any use of dowel connectors and bonding agent gives excellent bond between old to new concrete.

- When use of structure is change at that time this type of jacketing technique is more advantageous.

**(b) Repaired and Strengthened Beams**

- For smooth surface repaired and strengthened beams, highest load carrying capacity has been observed for beam using combined dowel connectors and bonding agent with micro-concrete as compared to other beams.

- For smooth surface repaired and strengthened beams, higher displacement at higher load has been observed for beam using combined dowel connectors and bonding agent with micro-concrete as compared to other beams.

- For smooth surface repaired and strengthened beams, higher strain has been observed at higher load for beam using combined dowel connectors and bonding agent with micro-concrete as compared to other beams.

- For smooth surface beams repaired by means of grouting and strengthened by jacketing, combined use of dowel connectors and bonding agent with micro-concrete gives good bond between old to new concrete.

- For chipped surface repaired and strengthened beams, highest load carrying capacity has been observed for beam with only micro-concrete and without dowel connectors and bonding agent as compared to other beams.

- For chipped surface repaired and strengthened beams considerable higher displacement at higher load has been observed for beam with only micro-concrete and without dowel connectors and bonding agent as compared to other beams.

- For chipped surface repaired and strengthened beams, higher strain at higher load has been observed for beam with only micro-concrete and without dowel connectors and bonding agent as compared to other beams.

- Use only micro-concrete for chipped surface jacketed beam without any use of dowel connectors and bonding agent gives excellent bond between old to new concrete.

- Ultimate load carrying capacity of strengthened and repaired and strengthened beams has been observed in same range of 250 kN to 310 kN which show that jacketing is more suitable for damaged beams.

- For damaged structure, repairing of beams by means of grouting is more effective for crack filing and strengthening by this type of jacketing technique is more advantageous.

## 7.3 Recommendations for Future Scope of Work

- Experimental work can be extended further by using different jacketing techniques like use of bent down bars, welding stirrups end together for RC beams.
- Instead of micro-concrete Jacketing can be done using different material like pre-placed aggregate concrete, shotcrete etc for RC beams.
- Comparative performance of jacketed beam under different loading condition can be evaluated.

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# Appendix A

# List of Papers Communicated

- Sachin S. Raval and Dr. Urmil V. Dave , “VARIOUS METHODS OF JACKETING FOR RC BEAMS”, 8th Biennial Conference (SEC), SVNIT, Surat, India, 19-21 December 2012. (Abstract Communicated)

- Sachin S. Raval and Dr. Urmil V. Dave , “VARIOUS METHODS OF JACKETING FOR REPAIRED RC BEAMS”, 3rd International Conference, NUiCONE - 2012, Departmet of Civil Engineering, Nirma University, Ahmedabad, 6 - 8 December 2012. (Abstract Communicated)