BEHAVIOUR OF FERROCEMENT ENCASED RC COLUMNS UNDER CONCENTRIC LOADING

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Submitted by

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CERTIFICATE

I hereby declares that the thesis entitled "**Behaviour Of Ferrocement Encased Rc Columns Under Concentric Loading**", is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering in Structural Engineering** at **Thapar University, Patiala** under the supervision of **Dr. Prem Pal Bansal,** Assistant Professor, Civil Engineering Department, Thapar University, Patiala. The matter embodied in this report has not been submitted in partial or full to any other university or institute for the award of any degree.

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It is certified that the above statement made by the student is correct to the best of my/our knowledge and belief.

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Ashish Awasthi

ABSTRACT

Reinforced concrete structures show excellent performance in terms of structural behavior and durability except for those zones that are exposed to severe environmental influences and high mechanical loading. Reinforced concrete is a commonly used construction material. RCC as a construction material has come into use for the last one century. In India RCC has been used extensively in the last 50 to 60 years. As with time the codes are upgraded for different reasons, the structures which were constructed on the bases of old codes may have some deficiencies according to the new codes. Change in use or higher loads and performance demands require modifications and strengthening of structural elements. Replacement of damaged structural elements is difficult and cost intensive task and replacement of a particular structural element may lead to the integrity of the connecting members. Retrofitting of a damaged structural element is one of the best solutions instead of replacing it. Retrofitting may be carried out on a global basis by adding extra load resisting elements or it can be done on a local basis by retrofitting the existing structural elements. From all global and local retrofitting techniques, jacketing construction is most preferred method of retrofitting. There are various composite materials available for jacketing of structural elements. Among all of them jacketing with ferrocement confinement is the oldest, efficient and economical technique of retrofitting or re-strengthening of deteriorated and weak columns.

Ferrocement is a form of thin wall reinforced concrete using wire mesh and high strength mortar. Small diameter of wires used as reinforcement, leads to a higher specific surface, providing homogeneity to the ferrocement. Closely spaced wires provide more ductility and energy absorption capacity. Column is a most important member in a framed structure and failure of this member may lead to the collapse of whole structure. The present study focused on the improvement in ferrocement jacketing technique in case of square columns and effect of different percentage of ferrocement jackets in case of circular columns.

In case of square columns two different approaches are taken into account; i.e. (a) strengthen all the corners (b) reducing stress concentration at the corners. The stress concentration at the corners is reduced by making the corners rounded. Further these two approaches are used in two types of ferrocement jacketing; i.e. (i) three layer ferrocement jacketing and (ii) single layer ferrocement jacketing and two extra layer of wire mesh at all corners. In case of circular column different percentage of wire mesh is used for ferrocement jacketing. Circular columns are confined with single, double and three layers of GI wire mesh.

In this study total 27 samples were casted out of them 15 were square and 12 were circular. The columns were confined using ferrocement after 7 days of curing and left for curing for further 28 days. After the completion of curing period all the specimens were tested under concentric compressive loading. From the results, it is observed that the load carrying capacity of square columns with rounded corners can be increased by 82.29% on confining the samples with three layer of ferrocement jacket. Similarly the load carrying capacity of square columns (sharp edges) confined with three layer of GI wire mesh, square column (sharp edges) confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners, square column (rounded corners) confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners, also increased by 68.01%, 53.13%, and 58.20% respectively. In case of circular samples the load carrying capacity of columns confined with one layer, two layers and three layers of GI wire mesh can be increased to 46.50%, 73.66%, and 132.51% respectively. The results showed that different techniques of retrofitting also enhance the ductility of column.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced concrete structures show excellent performance in terms of structural behavior and durability except for those zones that are exposed to severe environmental influences and high mechanical loading. Reinforced concrete is a commonly used construction material. RCC as a construction material has come into use for the last one century. In India RCC has been used extensively in the last 50 to 60 years. During this period we have created large number of infrastructural assets in terms of buildings, sport stadium, and bridges etc., which are lifeline for civilized society. These have been constructed with huge investment of resources. We can never dream of recreating such assets out of some degree of national resources. So it is essential to maintain them in functional condition.

The structures are constructed based on the specifications given in standard codes to meet the service life. As with time the codes are upgraded for different reasons, the structures which were constructed on the bases of old codes may have some deficiencies according to the upgraded codes. Change in use or higher loads and performance demands require modifications and strengthening of structural elements. Similarly a large stock of existing structures are deteriorated with use and time and might have passed their design life and require retrofitting and rehabilitation. The structures are also susceptible to earthquake, flood, cyclone, environmental pollution, chloride attack, carbonation, inadequate design and faulty construction. The environmental stresses like humidity, air and water pollutants also cause corrosion and develop cracks leading to the failure of structural element. Replacement of damaged structural elements is difficult and cost intensive task and replacement of a particular structural element may lead to the integrity of the connecting members. Retrofitting of a damaged structural element is one of the best solutions instead of replacing it. Retrofitting is a process by which the strength or load carrying capacity of a structure or structural member is increased to a significant range.

Retrofitting may be carried out on a global basis by adding extra load resisting elements or it can be done on a local basis by retrofitting the existing structural elements. Global retrofitting of a RC structure can be done by the following methods:

a. Adding shear walls
b. Adding infill walls
c. Adding bracings
d. Adding wing walls
e. Wall thickening
f. Base isolation
g. Mass dampers

Local retrofitting is a technique in which an element of a structure is retrofitted and this can be carried out by following methods:

a. Jacketing of columns
b. Jacketing of beams
c. Jacketing of beam column joint
d. Strengthening of individual footing

From all above global and local retrofitting techniques, jacketing is most preferred method of retrofitting that can be applied by the following techniques:

1. Confinement with external steel caging techniques
2. Confinement with ferrocement
3. Confinement with fibre reinforced polymers such as carbon fibres, glass fibre polymer etc.

Retrofitting with ferrocement confinement is the oldest and economical technique of retrofitting. Lots of research work has done on ferrocement confinement and it is found an effective technique to use ferrocement confinement for retrofitting of structural elements. The unique properties of ferrocement such as water proof, fire resistance, low self weight, durability and crack resistance makes it an ideal material for wider applications. Due to low cost and less skilled labour requirement in ferrocement construction, it is preferred in various rehabilitation projects.

1.2 FERROCEMENT TECHNOLOGY

The term ferrocement, also referred to as ferro concrete, is most commonly applied to a mixture of Portland cement and sand applied over layers of woven or expanded steel mesh and closely spaced small-diameter steel rods rebar. It can be used to form relatively thin, compound curved sheets to make hulls for boats, shell roofs, water tanks, etc. It has been used in a wide range of other applications including sculpture and prefabricated building components. It is a thin construction element with thickness in the order of 10-25 mm. It is a type of thin reinforced wall commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh (ACI Committee 549-R97, 1997). It uses rich cement mortar with low water cement ratio usually 0.4 and small diameter wire mesh layers. Admixtures like silica fume, super plasticizers and non-metallic fibres may be used for better results. This makes ferrocement structures high strength to weight ratio. Therefore, self-weight of ferrocement structure is very less as compared to RCC. It requires no skilled labour for casting, and employs only little or no formwork. In ferrocement, cement matrix does not crack since cracking forces are taken over by wire mesh reinforcement immediately below the surface (Desai, 2011). A structure involving complex curvatures can be constructed in a reliable manner using ferrocement technology, giving free reign to architectural expression. Ferrocement construction technology is being popularized throughout the world in countries like Canada, USA, Australia, New Zealand, United Kingdom, Mexico, Brazil, the former USSR, Eastern European countries, China, Thailand, India, Indonesia, and in other developing countries due to its uniqueness and versality (Shannag and Ziyyad, 2007). Ferrocement is in great demand in construction industry due to its various applications in structural members like columns, beams, slabs, walls, floors, window and door frames, water and soil retaining structures etc. Ferrocement can be fabricated into any desired shape or structural configuration that is generally not possible with masonry, RCC, or steel. Based on these advantages, ferrocement can be effectively utilized for strengthening or retrofitting such as water tanks, boats, housing wall panels, roofs, form work etc.

1.2.1 Constituents of Ferrocement

Ferrocement is a composite thin element which is constructed of building materials steel reinforcing mesh or wire mesh, cement, fine aggregate (sand) and water (ACI Committee 549R-97) and each of these materials are separately described in this section below.

a) Steel reinforcing mesh

Ferrocement uses layers of continuous/ small diameter steel wire/ weld mesh netting (metallic or non-metallic) as reinforcement with high volume fraction of reinforcement (2 to 8%) and the specific surface of reinforcement is considerably higher for ferrocement than for RCC. Also, the reinforcing steel wire mesh has openings large enough for adequate bonding; the closer distribution and uniform dispersion of reinforcement, transform the otherwise brittle mortar into a high performance material distinctly different from reinforced concrete. Skeletal steel rods/wires/strands are used as spacer material and to form the skeleton of the shape of the structure to be built, around which the mesh layers are later attached (Naaman, 2000). The type of wire mesh available in market are square, expanded, hexagonal mesh as shown in fig. 1.1.

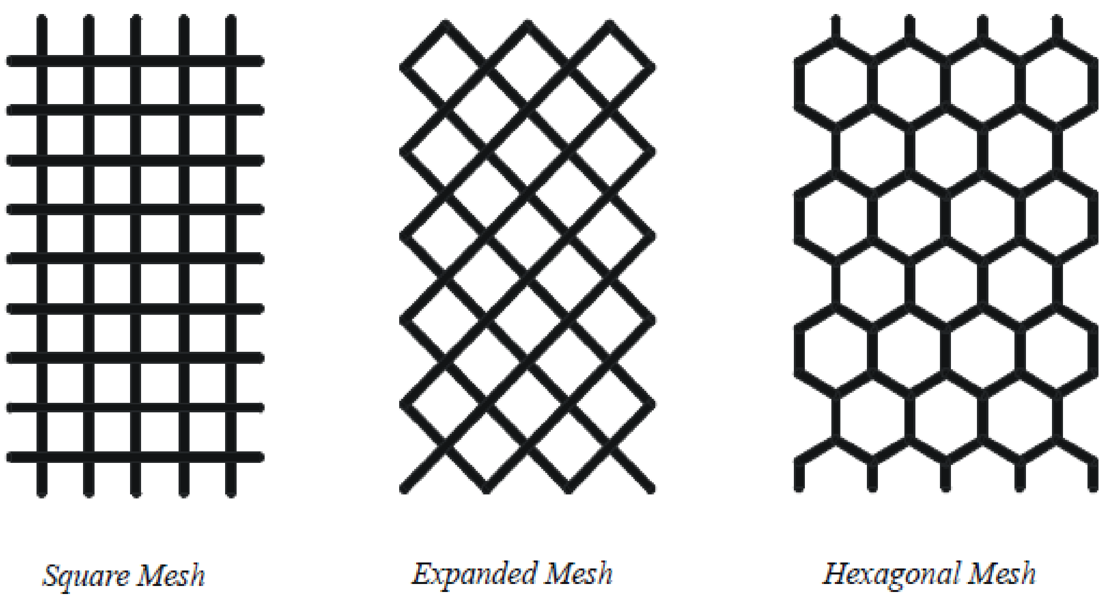


Fig. 1.1 Types of Wire Mesh

b) Cement

Portland cement is generally used in ferrocement. The type of cement should be selected according to the need or environment in which the structure is constructed. Mineral admixtures, such as flyash, blast furnace slag, or silica fumes, may be used to maintain a high volume fraction of fine filler material as well as to enhance the properties at wet and hardened state.

c) Aggregate

Only fine aggregate is used in ferrocement. Normally, the aggregate consists of well graded fine aggregate (sand) that passes a 2.34 mm sieve; and since salt-free source is recommended, sand should preferably be selected from river-beds and be free from organic or other deleterious matter. Good amount of consistency and compatibility is achieved by using a well-graded, rounded, natural sand having a maximum top size about one-third of the small opening in the reinforcing mesh to ensure proper penetration. The moisture content of the aggregate should be considered in the calculation of required water (Naaman, 2000).

d) Water

In ferrocement, the water used for mixing cement mortar should be fresh, clean and fit for construction purposes; the water of pH equal or greater than 7 and free from organic matter silt, oil, sugar, chloride and acidic material

e) Admixtures

To enhance the strength of ferrocement mortar matrix, polymers can be added to concrete in green stage and after construction, surface coatings like polymer based waterproofing coatings, cement based paint coating can be done.

1.2.2 Applications of Ferrocement

a) Structural applications of ferrocement

Ferrocement can be used in various structural members subjected to different type of stresses. As a compression member, hollow columns with horizontal stiffners can be cast in ferrocement. Columns or walls in concrete, RCC, stone or brickwork can be encased in ferrocement to increase their strength due to confinement. Members subjected to membrane stresses like shells, domes, pyramids can be cast in ferrocement very easily; and being a homogenous material, full section of member is utilized in resisting the membrane stresses. A greater use could be made of ferrocement in water-retaining constructions. Because of its very small crack widths under service load and it superior extensibility, ferrocement provides excellent leakage characteristics for applications in water tanks.

b) Roofing applications

Ferrocement is an economic alternative material for roofing. Flat or corrugated roofing system is quite popular.

c) Need for repair of RCC structures

Some major reasons for the deterioration of RCC structures are cracking (due to incorrectly made construction joints, poor compaction, segregation, poor curing and high water content) and spalling (due to corrosion in the reinforcement bars accelerated by a lack of adequate cover). The cracks in the concrete may be developed due to wrong design of structure or due to poor quality of materials used, and this will facilitate internal corrosion of steel reinforcement used in RCC elements; the cracks in course of time deepens up due to increase in corrosion and subsequently, peeling of concrete cover or spalling of concrete takes place. Use of proper repairing materials and methods of damaged or deteriorated RCC structures is a necessity not only to serve the intended service life but also assure the safety of buildings (Masood et al. 2003). Ferrocement is generally used for repairing or retrofitting of structural members by jacketing techniques.

1.2.3 Ferrocement Confinement

Ferrocement confinement is done around defective circular or square/rectangular RCC columns in order to enhance the strength, ductility and energy absorption capacity of existing concrete columns. A jacketing layer of 30 mm is created around the RCC columns with ferrocement is done in order to increase its load carrying capacity. This confinement work also protects the existing reinforcement, provides water tightness and prevents ingress of the aggressive species to the surface of original concrete or steel surface. Ferrocement not only increases the performance/ function of structures but also enhances the appearance of the existing RCC structure. The repair in the structural elements using ferrocement can withstand for long years without cracking provided the mortar used is of proper proportion using good quality materials, and the wire mesh is of anti-corrosive coating type (Masood et al., 2003).

1.2.4 Advantages of Ferrrocement Technology

- **Ferrocement is an isotropic material** up to 40% of the yield and its density is about 2750 kg/m3. RCC material is a heterogeneous material (density 2500 kg/m3) consists of voids and capillaries. Therefore, water and other gases easily entrapped in the concrete material which cause crack formation, spalling and corrosion of reinforcement. Moreover, the cracks formed over RCC structures are wide and deep whereas minute and shallow cracks are formed in the ferrocement structures. Structural members of ferrocement remain free of voids and capillaries hence remain corrosion resistant and water proof due to these properties.
- **Ferrocement has high strength to weight ratio**. Ferrocement is thin section high strength structural material highly waterproof, crack formation resistant, energy absorbing material. It is manufactured with high cement content, low water cement ratio around 0.4, wire mesh layers, light structural steel, admixtures mainly silica fume super plasticizers, non-metallic fibres, particularly when ferrocement is cast-in-situ. Therefore self-weight of ferrocement structure is very less as compared to RCC.

- **Ferrocement is highly ductile, resilient, energy absorbing material.** When put under load it develops cracks at a much higher value after the elastic limit. Because of this property a ferrocement structures frame will not collapse like RCC and therefore there will be least loss of life and property. Ferrocement structures do not collapse but get deformed. A large number of such structures as compared to RCC can be easy to repair. The debris formation will also be the less.

1.3 COLUMN

Column is the most important element in a frame structure because it carries the load coming from beams and transfer that load to the foundation. So failure of this element may lead to the collapse of the whole frame structure. A reinforced concrete column is a structural members designed to carry compressive loads, composed of concrete with an embedded steel to provide reinforcement.

Retrofitting or reconstruction of the damaged column is the necessary task to prevent the further damage to the whole structure. So it is utmost important to increase the load carrying capacity and impart ductility to the concrete, which can be done by external confinement of column. The strength of the column is greatly influenced by the length.

1.3.1 Classification of Columns

a) Classification on the basis of shapes

A column can be cast into various shapes. Generally used shapes are:

- Square
- Rectangular
- Circular
- Hexagonal

b) Classification on the basis of slenderness ratio

Slenderness ratio is the ratio of length to diameter/ least lateral dimension. On the basis of slenderness ratio the columns are classified into two categories as:

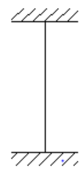
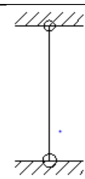
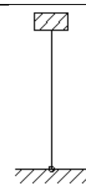
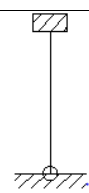
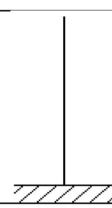
- Short columns
- Long columns

If the value of slenderness ratio is less than 12, the column is considered as Short Column and if the value is greater than 12, it is considered as a Long Column. The short column has more load carrying capacity than the long column of the same cross section.

The mode of failure of the short column is mostly in compression whereas the long columns fail with a buckling mode. The slenderness ratio governs the mode of failure. In compression mode of failure, the column has a tendency of failure either near the top or bottom of the column with a brittle fracture followed by the rupture of the core concrete. Long columns fail near the middle of the length showing large lateral deflection as compared to small deflection exhibited by the short columns.

c) Classsification on the basis of design

On the basis of design requirements columns can be categorized into two types:

Degree of end restraint of compression member	**Symbol**	**Theoretical value of effective length**	**Recommended value of effective length**
Effectively held in position and restrained against rotation in both ends		0.50 *l*	0.65 *l*
Effectively held in position at both ends and restrained against rotation at one end		0.70 *l*	0.80 *l*
Effectively held in position at both ends but not restrained against rotation.		1.00 *l*	1.00 *l*
Effectively held in position and restrained against rotation at one end, and at the other restrained against rotation but not held in position		1.00 *l*	1.20 *l*
Effectively held in position and restrained against rotation at one end, and at the other end partially restrained against rotation but not held in position		-	1.50 *l*
Effectively held in position but not restrained against rotation at one end, and at the other end restrained against rotation but not held in position		2.0 *l*	2.00 *l*
Effectively held in position and restrained against rotation at one end, but not held in position nor restrained against rotation at the other end		2.00 *l*	2.00 *l*

Where “ *l* ” is the unsupported length of the compression member.

Fig. 1.2 Effective Length of Compression Members (IS 456-2000)

- Spiral columns
- Tied columns

Spiral columns are cylindrical columns with a continuous helical bar wrapping around the column. The spiral acts to provide support in the transverse direction and prevent the column from barreling. Whereas Tied columns have closed lateral ties spaced approximately uniformly across the column. The spacing of the ties is limited in that they must be close enough to prevent barreling failure between them, and far enough apart that they do not interfere with the setting of the concrete.

1.3.2 Effective Length of the Column

The effective length of the column depends on the degree of fixity of the ends of the columns. IS 456:2000 provides recommendations for the effective length of the compression members as shown in Fig. 1.2. The different end conditions govern the behavior of column in different loading conditions.

1.4 OBJECTIVES

In recent years, strengthening of reinforced concrete elements, such as beams, columns,etc.,has given enormous emphasis as the failure of these elements could catastrophically fail the entire structure. In the past few decades, ferrocement has been used as restrengthening material for its better crack resisting properties. It is observed from the literature that strengthening the square columns (sharp edges), with ferrocement jacketing increases the load carrying capacity of column, but maximum cracks during loading and after failure were observed at corners of columns. To minimize these cracks at corners it is required to strengthen the corners or to reduce the stresses at corners.

This research is aimed to evaluate the effectiveness of wire mesh confinement in strength deficient columns. This was achieved by comparing the behavior of ferrocement confined columns with that of the reinforced unconfined columns. For this study the following objectives are framed:

- To study the improvement in load carrying capacity and ductility of square columns after strengthening the corners with ferrocement jackets.

- To study improvement in load carrying capacity and ductility of square columns by reducing the stress concentration at corners and strengthen with ferrocement jacketing.
- To study the effect of ferrocement confinement with different percentage of wire mesh in square coluns.
- To study the improvement in load carrying capacity of circular columns confined with different percentage of wire mesh (i.e. one, two and three layer).

CHAPTER 2
REVIEW OF LITERATURE

2.1 GENERAL

Ferrocement, a thin element, is used as a building construction as well as a repair material. It is a thin construction element with thickness in the order of 10-25 mm. Ferrocement uses rich cement mortar. No coarse aggregates are used and the reinforcement consists of one or multiple layers of wire mesh. The structures made up of ferrocement are economical and light in weight. There are many structures built of ferrocement--housing units, shell roofs, water tanks and swimming pools, biogas digesters, silos, food storage units, and for some specialized applications such as floating marine structures for which reinforced concrete is too heavy, ferrocement is a preferred choice over reinforced concrete (Naaman, 2000; Hago et al., 2005; Abasolo et al., 2009). From last some decades ferrocement is used for repair or retrofitting work. In ferrocement, due to small spacing of reinforcement wire mesh it allows better dispersion of the load on the surface and cracks are minimized (Desai, 2011). Also, due to the openings of the wire mesh, it allows the adequate bonding, closer distribution and uniform dispersion of the reinforcement making the brittle mortar into a high performance material distinctly different from reinforced concrete. This is in great demand due to its one main property i.e. to be moulded in any desired shape.

2.2 RESEARCH ON FERROCEMENT PROPERTIES

Yaqub et. al*. *(2013) An experimental study carried out to compare the effectiveness of ferrocement and fibre reinforced polymers (FRPs) jackets for the repair of post-heated square and circular reinforced concrete columns. The suite of test specimens comprised (a) non-heated and non-repaired; (b) post-heated and non-repaired and (c) post-heated and repaired, columns. Glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP) and ferrocement jackets were used to repair the heated columns. All the columns were tested under axial compression.

It is well-known that reinforced concrete columns which have been subjected to a fire will lose a major part of their compressive strength and stiffness. These two factors (strength and stiffness) are a major concern relating to the safety of concrete structures after fire. Generally, post-heated concrete structures are capable of being repaired economically rather than completely demolished and re-built. In their study they have done experiment on square and circular columns. A total of sixteen reinforced concrete columns (eight square and eight circular) were tested. In order to undertake the investigation, the columns were divided into (a) non-heated and non-repaired, (b) post-heated and non-repaired, and (c) post-heated and repaired columns. The rate of heating was chosen to ensure that any damage caused by a high thermal gradient through the cross-section of the column is minimised. Subsequently, the post-heated/repaired columns were repaired with a single layer of glass or carbon fibre reinforced polymers or a ferrocement jacket comprising four layers of wire mesh and mortar. The test results showed that the FRP jackets increased the compressive strength, ductility, deformation ability and energy dissipation capacity of post-heated columns but did not increase the stiffness. However, the ferrocement jackets enhanced both the strength and stiffness of the post-heated columns. It is concluded that a possible combination of ferrocement and FRP jackets is the optimum solution to restore the required strength, stiffness and ductility following structural damage from a fire.

Kaish et. al. investigate the behaviour of ferrocement confined square RC column, eight square columns (six jacketed columns and two non-jacketed columns (NJ)) were tested under small eccentric compression load until failure. Various jacketing techniques such as; (i) Square jacketing with single layer wire mesh (denoted as SL); (ii) Square jacketing with single layer wire mesh and rounded column corners (denoted as RSL); and (iii) Square jacketing with single layer wire mesh and two extra layers mesh at each corner (denoted as SLTL). In this study, fresh Ordinary Portland cement (OPC) of grade 43 confirming Type I of ASTM C-150 was used for preparing test specimens.

At ultimate loads It is seen that the load carrying capacity of jacketed specimens is higher than those obtained from benchmark specimens. The increased magnitudes of loading are obtained as 30.91%, 47.76% and 33.35% for SL, RSL and SLTL type specimens, respectively. Strong crack arresting properties of ferrocement could be the reason for resisting higher load. It is seen that SL and SLTL type specimens fail almost the same load though SLTL type carries two extra layers wire mesh at all corners. RSL type specimen fails in higher load than the SL and SLTL type specimens. Vertical and lateral deflections of both jacketed and non jacketed specimens are given in Table 3. It is seen that the vertical and lateral deflections of SL, RSL, SLTL type specimens are more than those obtained in non jacketing type specimens. The increased magnitudes of vertical and lateral deflections for SL, RSL, SLTL type specimens are obtained as 44.41%, 83.68%, 67.37% and 23.57%, 80.71%, 65.71%, respectively, over NJ type specimen. About the failure patterns it is seen that non-jacketed column starts to fail by crushing of concrete at the point of application of load, whereas jacketed column starts to fail from ferrocement encasement. Ferrocement jacket separation was also observed in SL and SLTL type specimens. In case of RSL type specimen, no jacket separation was found. More cracks were appeared in RSL type specimens than SL and SLTL type specimens, which indicate that RSL type jacketing is more ductile than SL and SLTL type specimens.

Malhotra (2013) in the experimental part of his work, a total of 27 column specimens with three different slenderness ratios (S.R.) were casted. Three slenderness ratios were considered (i) S.R.=3; (ii) S.R.=7; and (iii) S.R.=15. These specimens were further divided in to three categories. First category consisted of three unconfined control columns from each size group, second category consisted of three column confined with ferrocement using one layer of wire mesh and third category consisted of three columns confined with ferrocement using two layers of wire mesh. All the columns were tested under monotonic uniaxial compression loading. The results showed that ferrocement confinement increased the load carrying capacity and stability of the column by decreasing the lateral deflection. The increase in slenderness ratio resulted in decrease of strength of the ferrocement confinement. It was also observed that in the ferrocement the wire mesh is more effective up to one or two layers.

Shannag and Mourad (2012) have done a laboratory investigation to develop high strength cementitious matrices for casting thin ferrocement laminates ideally suited for structural repair/retrofit. The developed high strength mortar matrices contain various combinations of silica fume and fly ash, and provide a good balance between flowability and strength. The matrices developed had a 28-day compressive strength range from 48 to 64 MPa with a corresponding flow range from 129% to 138%. The developed high strength mortar was used in producing ferrocement jackets for cylindrical stubs to examine its performance and efficiency when the stubs are subjected to axial loads. The developed high strength ferrocement laminates seem to provide appreciable increase in load carrying capacity, lateral confinement and ductility. In terms of ferrocement efficiency, the stubs wrapped with the laminates containing 2 and 4 layers of welded wire meshes, WWM, showed about 16% and 29% increase in axial stress respectively, with a corresponding increase in axial strain of about 32% and 70% respectively. According to their study, high strength ferrocement laminates containing a specific number of welded wire meshes can be considered as a promising material for maintenance and rehabilitation of concrete structures, especially when using high strength and flowable mortar with WWM complying with ferrocement specifications.

Mourad and Shannag (2012) The experimental program consists of testing one third scale square (150 X 150 mm) column specimens with a height of 1000mm in three phases as follows; Phase 1: Control column specimens without any preloading and without ferrocement jackets, Phase2: Jacketed column specimens without any preloading but with ferrocement jackets, Phase 3: strengthened preloaded column specimens include column strengthened with ferrocement jackets after preloading them with 60%, 80%, and 100% of their ultimate axial strength.

The ferrocement jackets were prepared using two layers of welded wire mesh and covered with a flowable high strength mortar jacket using specially designed molds. Ferrocement jackets were applied to the unloaded column specimens after 28 days from the day of casting. While Ferrocement jackets were applied to the preloaded and failed columns after being tested to 60%, 80%, and 100% of their axial capacity. After the testing it is observed that jacketed specimen reported significant increase in both load carrying capacity and axial stiffness as compare to the control specimen; such increase are about 33% and 26% respectively. It can be observed that strengthened preloaded column specimen recorded higher load carrying capacity and axial stiffness as compare to the control but less than those from the jacketed column specimens. Results indicates that repairing tied reinforced concrete columns that were preloaded up to 60% and 80% of their ultimate load carrying capacity, caused 28% and 15% increase in load carrying capacity.

Kaish et. al.(2012) Experimental investigations were carried out on non-jacketed, conventional ferrocement jacketed and improved ferrocement jacketed square RC short column specimens to see the effect of improved ferrocement jacketing over the non jacketed and conventional ferrocement jacketed specimens. Entire study was done in two phases under monotonically increasing load. In the first phase, 17(length, L = 600 mm, breadth, b = 100 mm with L:b = 6:1) column specimens with normal tie were tested under concentric mode of loading. In the second phase, 24 (L:b = 6:1) column specimens with seismic tie were tested under concentric mode of loading as well as eccentric mode of loading. Among 24 specimens of second phase, 12 specimens were tested under concentric mode of loading and the rest of 12 specimens were tested under eccentric mode of loading. Among all tested specimens, five specimens in the first phase and six specimens in the second phase were tested without any jacketing and were denoted as NJ. Four types of ferrocement jacketing were taken into consideration in this study. These are: (i) Square jacketing with single layer wire mesh (conventional square ferrocement jacketing denoted as SL); (ii) Square jacketing with single layer wire mesh and rounded column corners (denoted as RSL); (iii) Square jacketing with single layer wire mesh and shear keys at the center of each faces (denoted as SKSL) and (iv) Square jacketing with single layer wire mesh and two extra layers mesh at each corner (denoted as SLTL). Corner radius in type RSL was considered as approximately 12 mm in the first phase and 24 mm in the second phase. In type SKSL specimen, 2 mm (dia.) steel nails with nailing depth of 25 mm were used as shear keys at a vertical spacing of 50 mm along the length of the column specimens. In the first phase of experimental study, all four types of ferrocement jacketed column specimens were tested. However, in the second phase of testing, only type SL, RSL and SLTL jacketed column specimens were tested. Fresh Ordinary Portland cement (OPC) of grade 43 conforming Type I of ASTM C-150 was used for making both concrete and ferrocement mortars.

It is seen that the axial load carrying capacity of all jacketed specimens is higher than those obtained from the non-jacketed specimens tested under both concentric and eccentric modes of loading. Type SKSL specimen shows lower load carrying capacity than the type SL specimen in the first phase though both types of specimens contain same layer of wire mesh. This may be due to the effect of shear keys into the column that weakens the original column. In both first and second phases, type RSL specimen shows higher load carrying capacity than the type SL specimen under concentric mode of loading due to its rounding of column corners. Type SLTL specimens show the highest load carrying capacity over all types of jacketed specimens as well as non jacketed specimens as these specimens were prepared by providing two extra layers wire mesh at each corner with no decrement of original column cross section. This type of specimen shows 50% and 44.68% increased load carrying capacity over the non-jacketed specimen under concentric mode of loading in first and second phases, respectively. On the other hand, among all the jacketed and non-jacked specimens tested under eccentric mode of loading in the second phase, type RSL shows the highest load carrying capacity over other types of jacketed specimens as well as non jacked specimens. It shows 47.76% increased load carrying capacity than the NJ type specimens. It is seen that, all jacketed specimens show higher axial deflection than the non-jacketed specimens at ultimate load.

Xiong et. al. (2011) In order to significantly increase not only the load carrying capacity but also the ductility of existing circular concrete columns, a method to strengthen the columns with ferrocement including steel bars (FS) jacket was proposed. To evaluate the behaviour of the FS strengthening columns more objectively and thoroughly, a comparatively experimental study on uniaxial compression behaviours of concrete columns wrapt with three different confining systems, namely bar mat-mortar (BM), FS, and fibre reinforced polymer (FRP), was carried out. Fifty-one specimens were produced. The load–strain responses, failure modes, ultimate loads and ductilities of various strengthened columns were investigated. The experiment results showed that the mortar cover crack spaces of FS columns were basically equal to the wire mesh spacing, leading to the occurrence of much more cracks compared with that of BM columns. As a result, on the premise that the concrete compressive strength of the FS columns increased 30% compared with that of the BM columns, the ductility of the former reached about twice as that of the latter. When the confined concrete strength of FRP strengthened columns was similar to that of FS strengthened columns, the ductility, energy absorption capacity and deformation capacity of the former were obviously lower than those of the latter.

It is observed that the strength, ductility and energy absorption capacity of existing concrete columns can be simultaneously enhanced significantly by constructing additional ferrocement cage including steel bars. Due to the occurrence of much more cracks in the mortar layer of FS confined columns, the ductility of FS confined columns is obviously higher than those of BM or FRP confined columns.

Abdulllah and Takiguchi (2003), Presents behavior and strength of reinforced concrete (RC) columns strengthened with ferrocement jackets. A total of six identical reference columns were prepared and tested after being strengthened with circular or square ferrocement jackets. Other than the ratio of axial load, parameters studied include the jacketing schemes, and the number of layers of wire mesh. Unless failure occurred at an earlier stage of loading, the columns were tested under cyclic lateral forces and constant axial load. Test results show that by providing external confinement over the entire length of the RC columns, the ductility is enhanced tremendously. Also, test results of this investigation revealed that the design method, proposed earlier by the authors, is very effective. It was found that by providing circular ferrocement jacket that contained three layers of wire mesh, the brittle shear failure that occurs on the control specimen can be prevented, and the strengthened column shows extremely well in strength and ductility performance. It was also found that circular ferrocement jackets containing six layers of wire mesh can be used for repair damaged RC columns that have failed in shear.

2.3 RELEVANCE OF THE PRESENT STUDY

Brittle shear failure in RC columns, especially constructed before 1980s, has been identified as one of the main causes of structures' failure observed in the recent major earthquakes (Abdulllah and Takiguchi (2003)). Typical damage was attributed to the large spacing of tie in the columns, and the use of 90° hooks, even in conjunction with close tie spacing. Many other columns, although not damaged by the earthquakes and which have been properly designed and constructed in accordance with earlier building standards, had to be strengthened due to more stringent existing Building Code requirement. Such columns typically have problems such as insufficient ductility due to improper transverse confinement, and insufficient shear strength. Also, the hoops in existing columns were typically lap-spliced with a relatively small length without bending the tails of the hoops into the core concrete as required in the most modern seismic provisions. Such details cannot provide sufficient anchorage for hoops, when cover concrete spalls off. However, researches conducted in the past have shown that the compressive strength of core concrete, ultimate concrete compression strain and ductility of the strengthened column increased significantly if proper external confinement by mean of jacketing was provided (Abdulllah and Takiguchi (2003)). Therefore, retrofitting techniques usually involve methods for increasing the confining forces either in the potential plastic hinge regions or over the entire column.

Recent research works have shown that ferrocement jacket could be used as an alternative and effective technique to strengthen RC column with inadequate shear strength. Experimental and analytical studies on the confinement effect and failure mechanisms of ferrocement jacketed columns have been conducted over several years. This report is focused on the investigation of effects of ferrocement confinement on short square and cylindrical columns and their behavior under concentric load. The ferrocement confined square columns with sharp edges are compared with the ferrocement confined square columns with rounded edges. Further, the behaviour of confined columns was also studied with their respective controls. A total of 27 RC column specimens (15 square and 12 cylindrical) were casted and tested to failure under concentric axial loading.

CHAPTER 3

EXPERIMENTAL PROGRAMME

The object of the present thesis is to study the effect of ferrocement confinement on square and circular columns. Two different approaches are taken into account in case of square columns; i.e. (a) strengthen all the corners, and (b) reducing stress concentration at corners. In case of circular columns wire mesh percentage is varied. For experimental work total twenty seven specimens were casted out of them fifteen are square and twelve are circular in crossection. The load carrying capacity and ultimate deflection are observed and analyzed in the subsequent chapters.

3.1 MATERIALS

The main constituent materials cement, fine aggregates, reinforcement steel bars are used in the casting of columns. For ferrocement jacketing on column surface wire mesh, cement paste, and mortar is used. The detailed specifications of the material are as under:

3.1.1 Cement

Portland-Pozzolana Cement was tested and used for the concrete mix and mortar. The physical properties obtained from various tests are listed in Table 3.1. All tests are carried out in accordance to procedure laid in IS 1489 (Part 1): 1991.

3.1.2 Fine Aggregate

Local river sand was used as fine aggregate in concrete mix and cement mortar. The physical properties and sieve analysis results of sand are shown in Table 3.2 and Table 3.3.

3.1.3 Coarse Aggregate

Crushed stone aggregate of 10mm and 20mm size in ratio of 1:1 were used for concrete. The physical properties and sieve analysis results of coarse aggregate are shown in Table 3.4, Table 3.5 and Table 3.6.

3.1.4 Water

Potable water, free from organic matter, silt, oil, sugar, chloride and acidic material as per Indian Standard was used for the entire concreting and mortar application.

Table 3.1 Physical Properties of Cement

Sr. No.	Property	Value Obtained Experimentally	Value as per IS: 1489-1991
1	Standard Consistency	33.5	-
2	Fineness of cement as retained on 90 micron sieve ‘in %’	0.5	Min 0.1
3	Setting Time (in minutes) Initial Setting time Final setting time	120 450	Min 30 minutes Max 600 minutes
4	Specific gravity	3.0	
5	Compressive strength (N/mm2) 7 days 28 days	24.19 35.89	Min 22 Min 33

Table 3.2 Physical Properties of Fine Aggregate

Sr. No.	Property	Value Obtained Experimentally
1	Specific gravity	2.64
2	Fineness modulus	2.55
3	Water absorption	2.88%
4	Grading zone (based on percentage passing 0.6 mm)	Zone II

Table 3.3 Sieve Analysis of Fine Aggregate

Total weight taken = 1000 gm

Sr. No.	**Sieve Size**	**Mass retained (gm)**	**Percentage retained**	**Cumulative percentage retained**	**Percentage passing**
1	4.75mm	5	0.50	0.50	99.50
2	2.36mm	59	5.90	6.40	93.60
3	1.18mm	136	13.60	20.00	80.00
4	600 µm	243	24.30	44.30	55.70
5	300 µm	415	41.50	85.80	14.20
6	150 µm	122	12.20	98.00	2.00
7	Pan	20	2.00	100	0.00
	∑	**1000**			

Fineness modulus of fine aggregate = 2.55

Table 3.4 Sieve Analysis of Coarse Aggregate (20mm)

Total weight taken = 3000 gm

Sr. No.	**Sieve Size**	**Mass retained (gm)**	**Percentage retained**	**Cumulative percentage retained**	**Percentage passing**
1	40mm	0	0.00	0.00	100
2	20mm	28	0.93	0.93	100
3	10mm	287.6	95.87	96.80	99.07
4	4.75mm	75	2.50	99.30	3.20
5	pan	21	0.70	100	0.70
	∑	**3000**		**697.03**	

Fineness modulus of 20 mm coarse aggregate = 6.97

Table 3.5 Sieve Analysis of Coarse Aggregate (10mm)

Total weight taken = 2000 gm

Sr. No.	Sieve Size	Mass retained (gm)	Percentage retained	Cumulative percentage retained	Percentage passing
1	40mm	0	0	0	100
2	20mm	447	22.35	22.35	77.65
3	10mm	415	20.75	43.10	56.90
4	4.75mm	1055	52.75	95.85	4.30
5	pan	83	4.15	100	0
	∑	2000		661.15	

Fineness modulus of 10 mm aggregate = 6.61

Table 3.6 Physical Properties of Coarse Aggregate

Sr. No.	Characteristics	20 mm	10mm
1	Type	Crushed	Crushed
2	Specific gravity	2.68	2.75
3	Total water absorption (% age)	0.46%	0.53%
4	Fineness modulus	6.97	6.61

3.1.5 GI Wire Mesh

GI steel wire mesh of 0.45 mm dia. wires woven in square pattern was used for confinement in ferrocement. The grid size of mesh was 6mm x 6mm. Steel mesh is shown in Fig. 3.1. Table 3.7 shows the properties of GI wire mesh.

Fig. 3.1 GI Wire Mesh

Table 3.7 Properties of GI Wire Mesh

Diameter of wire	0.44mm-0.46mm
Mesh opening size	6mm x 6mm square mesh

3.1.6 Concrete Mix

Concrete mix is designed as per Indian Standard using the properties of materials as discussed in Table 3.1 to Table 3.6. The grade of design concrete mix was M20. The proportions of concrete design mix came out to be 1:1.69:1.71:1.669 (cement: sand: 10mm coarse aggregate: 20mm aggregate) by weight. The water cement ratio was kept 0.5. The cement concrete cubes 150mm x 150mm x 150mm were casted and compressive strength after 28 days was recorded 31.45 N/mm2. The concrete mix is prepared in a concrete mixer for proper mixing.

3.1.7 Mortar Mix

In ferrocement application cement sand mortar of ratio 1:3 was used. The water-cement ratio of 0.4 was used.

3.2 Casting of Reinforced Concrete Column Specimens

Cement Concrete is a mixture of well proportioned cement, coarse aggregates, fine aggregate and water. For the reinforcement steel bars of various diameters are used and for confinement with ferrocement GI wire mesh was used.

The grade of design concrete mix was M20. The columns specimens are casted in two groups: 15 square column specimens (100 X 100 X 600mm) and 12 cylindrical samples of 150mm diameter and 600 mm in length. Table 3.8 gives the detail column specimens.

3.2.1 Square Column Specimens

For experimental investigation total 15 column specimens were casted. Each square column specimen is reinforced with 4 bars of 8mm diameter as longitudinal reinforcement and 6mm diameter stirrups at 150mm c/c. The reinforcement used was Fe 500 grade.

Table 3.8 Detail of Column Specimens

Sr.No.	Description of Columns	Designation
1	Three square columns of size 100 x 100 x 600mm	CS
2	Three square columns (sharp corners) of size 100 x 100 x 600mm confined with three layer of GI wire mesh	RFCS
3	Three square column (rounded corners) of size 100 X 100 X 600mm confined with three layer of GI wire mesh	RFCRC
4	Three square columns (sharp corners) of size 100 x 100 x 600mm confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners.	RFCSC
5	Three square columns (rounded corners) of size 100 X 100 X 600mm confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners.	RFCRCC
6	Three circular columns of 150 mm dia.	CSC
7	Three circular columns of 150 mm dia. Confined with single layer of GI wire mesh.	CC-1
8	Three circular columns of 150 mm dia. Confined with two layers of GI wire mesh.	CC-2
9	Three circular columns of 150 mm dia. Confined with three layers of GI wire mesh.	CC-3

Fig. 3.2 and fig. 3.3 shows the reinforcement details of unconfined and confined square columns respectively.

After a curing period of 7 days, three columns were kept as control samples. Square specimens are further divided in two groups. In first group the corners of six specimens are made rounded with the help of hand grinder and in second group 6 specimen are kept with sharp corners. Six samples from each were hand chiseled to obtain a rough surface. After surface cleaning three specimens from each group were confined with three layers of GI wire mesh and three specimens from each group were confined with single layer GI wire mesh and two extra layers of GI wire mesh at corners. Fig. 3.4 shows the cross-sections of different type of ferrocement jacketed specimens.

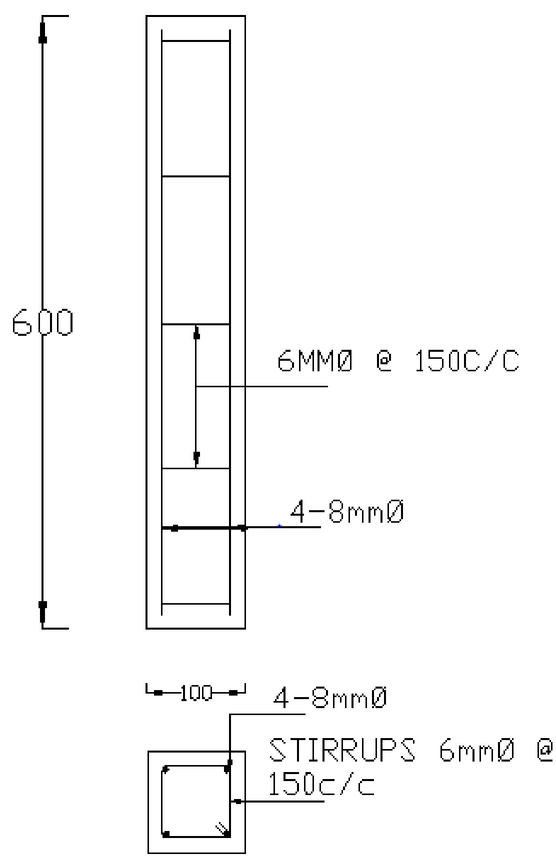


FIG.3.2 Reinforcement Detail of Unconfined Square Sample

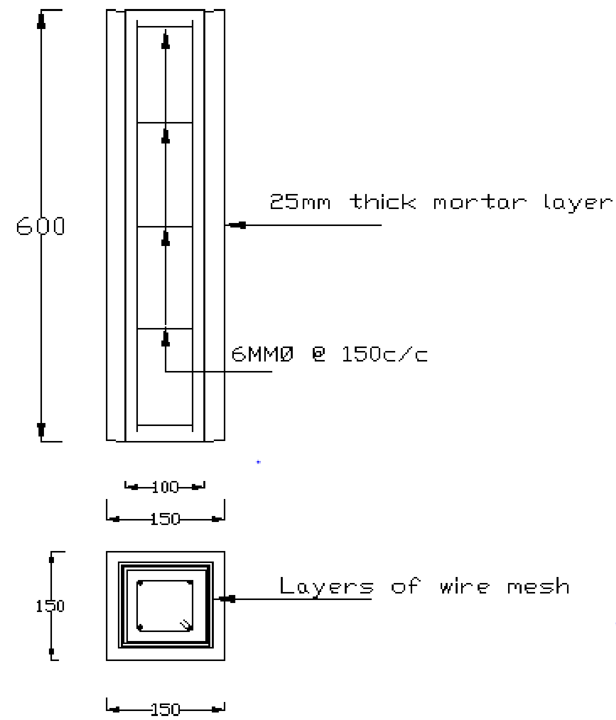


Fig. 3.3 Reinforcement Detail of Confined SquareSample

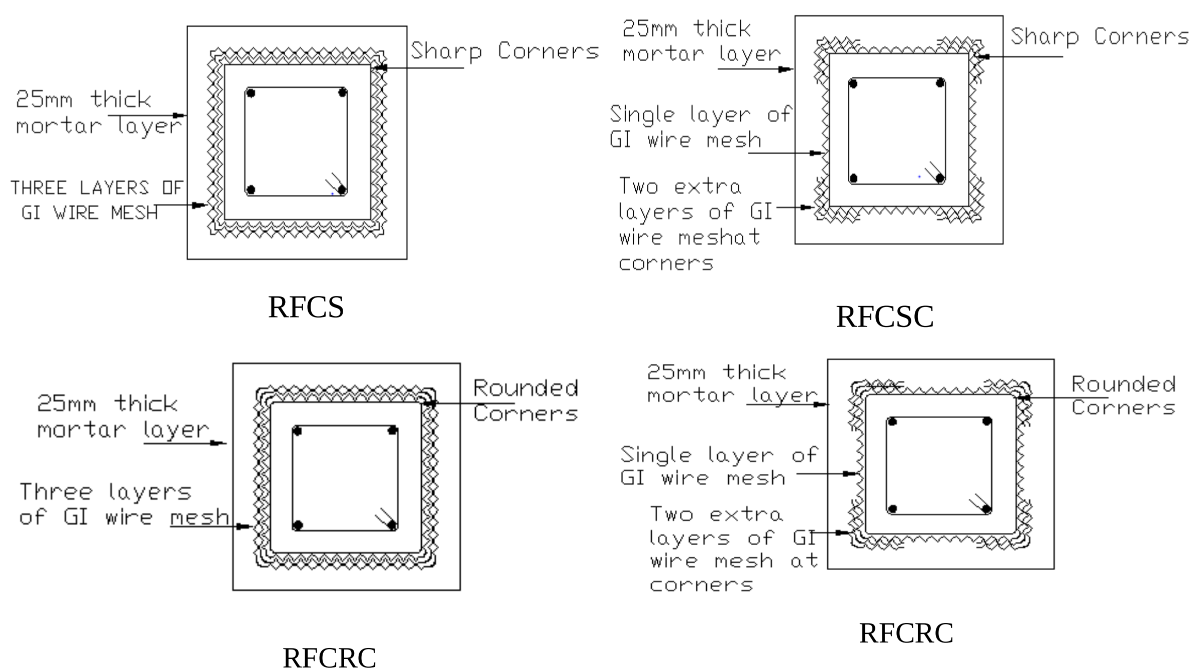
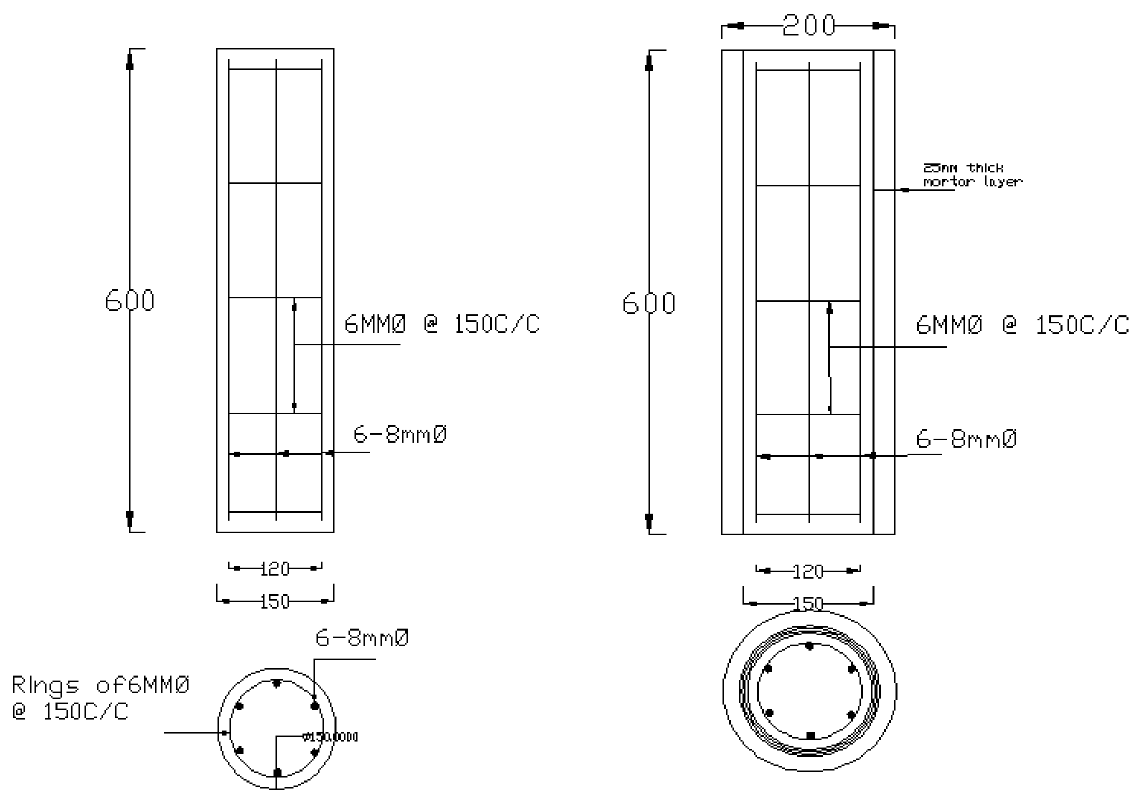


Fig. 3.4 Cross-section of Confined Square Columns

3.2.2 Cylindrical Column Specimens

For experimental investigation total 12 cylindrical column specimens of 150 mm diameter were casted. Each cylindrical column specimen is reinforced with six bars of 8mm diameter as longitudinal reinforcement and 6mm diameter stirrups at 150mm c/c. The reinforcement used was of Fe 500 grade. Fig. 3.5 shows the reinforcement detail of confined and unconfined cylindrical columns.

After a curing period of 7 days, three columns were kept as control samples. Nine samples were hand chiseled to obtain a rough surface. After surface cleaning three specimens were confined with single layer of GI wire mesh, three were confined with two layers of GI wire mesh and three were confined with three layers of GI wire mesh. Fig. 3.6 shows the details of different ferrocement jacketing techniques.



(Unconfined Samples) (Confined Samples)

Fig. 3.5 Reinforcement Details of Confined and Unconfined Cylindrical Columns

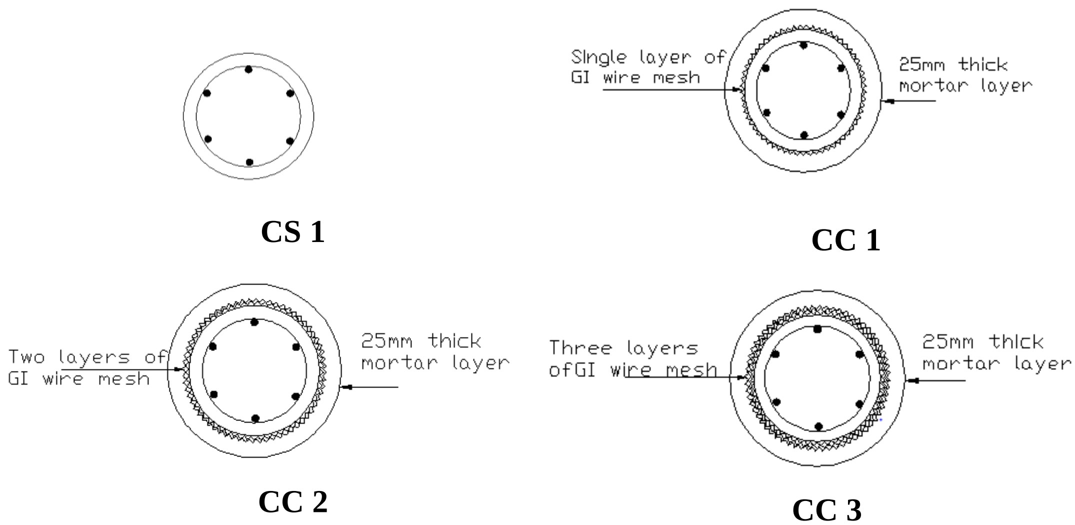


Fig. 3.6 Cross-Sectiom of Confined and Unconfined Cylindrical Columns

3.3 CONFINEMENT OF COLUMN SAMPLES WITH FERROCEMENT

3.3.1 Square Samples

After curing the samples for 7 days, they are confined with different techniques. For the confinement of the square RC column with ferrocement, the surface of the samples was hand-chiseled (fig. 3.7 (a)) and any dust or loose particles were removed with washing and allowed to air dry. In the first phase after surface preparation three column samples from each group were wrapped with three layer of GI wire mesh (fig. 3.7 (c)) followed by the application of cement paste (fig. 3.7 (d)) and layer of cement mortar 25mm thick over wire mesh to achieve a square width of 150mm x 150mm.

In the second phase after surface preparation three column samples from each group were wrapped with single layer of GI wire mesh and two extra layers of GI wire mesh at corners followed by the application of cement paste (fig. 3.7 (e)) and layer of cement mortar 25mm thick over wire mesh to achieve a square width of 150mm X 150mm. In the first phase the corners of six specimens were made rounded with hand grinder (fig 3.7 (b)). Fig. 3.7 shows the steps occurred in confinement of square columns.

(a) Surface Preparation

(b) Sample with Rounded Corners

(c) Three layer GI Wire Mesh Jacketing

(d) Application of Cement Paste

(e) Corner Restrained Sample

(f) Ferrocement Confined Sample

Fig. 3.7 Confinement of Square Columns

3.3.2 Cylindrical Samples

After completing a curing period of 7 days, the specimens are confined with different techniques. For the confinement of the cylindrical RC column with ferrocement, the surface of the samples was hand-chiseled and any dust or loose particles were removed with washing and allowed to air dry. Cylindrical samples are divided into three groups with three samples in each. After surface preparation three column samples from each group were wrapped with single layer of GI wire mesh, three samples were wrapped with two layer of GI wire mesh, and three samples were wrapped with three layer of GI wire mesh followed by the application of cement paste and layer of cement mortar 25mm thick over wire mesh to achieve a diameter of 200mm.

Proper curing is necessary to develop the required strength of the mortar. A curing period of 28 days is suggested; however, at least curing in the first two weeks is essential and should start 24 hours after final application of the mortar to avoid shrinkage cracks. Fig. 3.8 shows the confinement of cylindrical columns

(a) (Sample with Wire Mesh Jacketing)

(b) (Ferrocement Confined Sample)

Fig. 3.8 Confinement of Cylindrical Columns

3.4 Testing Procedure And Instrumentation

After completing the curing period of 28 days of test specimens, all specimens were kept in dry condition for few hours for attaining surface dry condition. The testing was carried out in a compression testing machine of capacity of 5000kN. Concentric compressive load was applied on all the specimens. Vertical and lateral deflections of all the specimens with respect to the load were recorded with the help of digital dial gauges. Lateral deflections were recorded at mid height and vertical deflections were recorded at the face where the load is applied. Dial gauges had an accuracy of 0.001mm. Test setup and the position of dial gauges and mode of loading is shown in fig.3.9

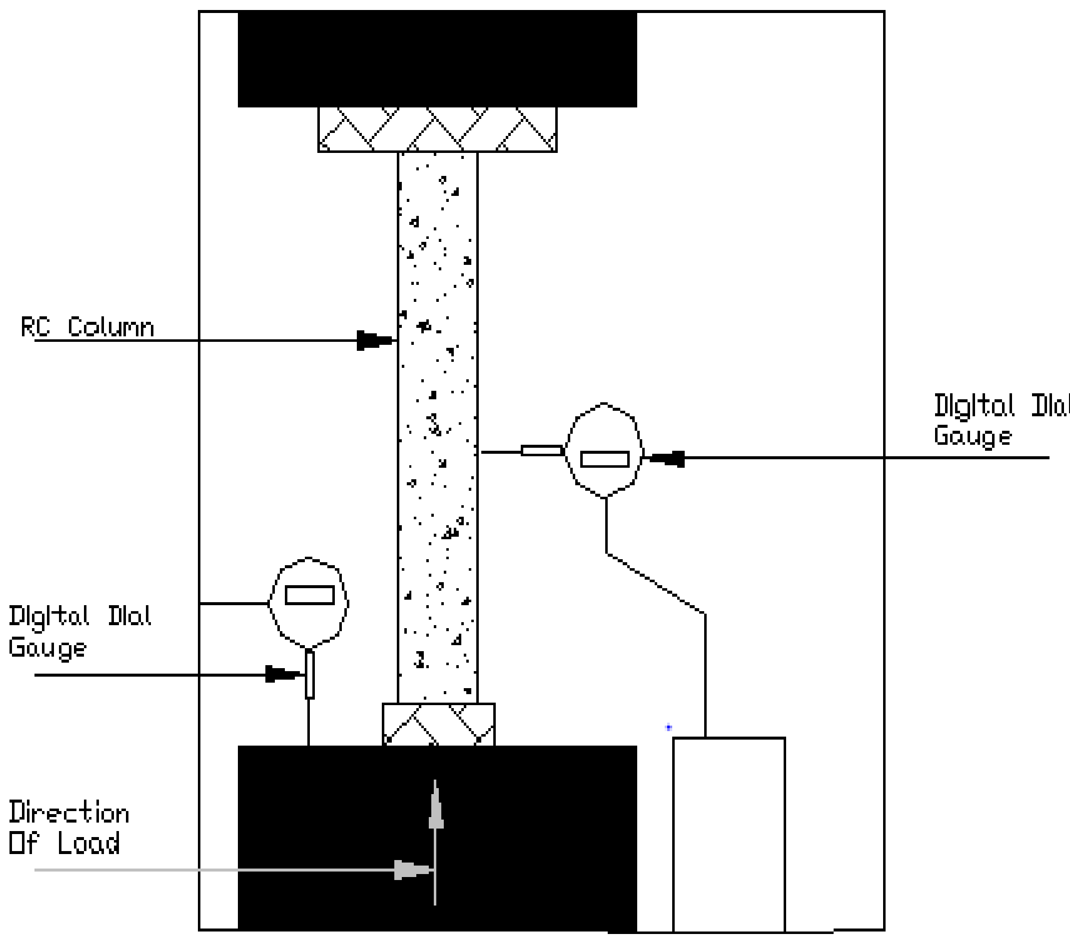


Fig.3.9 Detail of Test Setup

CHAPTER 4
RESULT AND DISCUSSION

4.1 GENERAL

The results obtained after testing of the specimens are discussed in this section. The average load-deflection graphs of three unconfined control concrete specimens (CS and CS 1), three square specimen (sharp corners) confined with three layer of GI wire mesh (RFCS), three square specimen (rounded corners) confined with three layer of GI wire mesh (RFCRC), Three square columns (sharp corners) confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners (RFCSC), Three square columns (rounded corners) of size confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners (RFCRCC), Three circular columns Confined with single layer of GI wire mesh (CC-1), Three circular columns of Confined with two layers of GI wire mesh (CC-2), Three circular columns Confined with three layers of GI wire mesh (CC-3) were prepared. All specimens were tested under concentric mode of loading. Load vs. deflection values, first crack load, crack pattern and ultimate load capacity were observed.

4.2 SQUARE COLUMNS

CS, RFCS, RFCSC, RFCRC, and RFCRCC column specimens were tested after a completion of 28 days curing period. The test results of these specimens discussed below.

4.2.1 Results of Control Sample (CS)

All the control specimens after completion of their 28 days curing period were tested in compression as mentioned in the experimental program in chapter 3. The specimens were tested up to their ultimate loads and their vertical deflection at the face of application of load and lateral deflection at mid height were measured by using digital dial gauges. As the load applied to the specimen, some low level cracking sound was heard. This may be due to micro cracking of the concrete. As the loading continued the specimen starts deforming vertically. At a load of 105kN some minor cracks were observed near the top of column and at a load of 262kN the load reaches the ultimate value. Some minor cracks were observed at the bottom also. Bursting of concrete is observed at the top of column.

As the column is a short column it fails from top and bottom by crushing. As negligible deflection at mid height was observed, so it is clear that the failure of column was due to crushing. The maximum vertical deflection observed was 3.27mm. The graph of load vs. vertical deflection is shown in fig. 4.1 and fig. 4.2 describes the crack pattern at the failure. From fig. 4.2(b) it can be seen that the cracks appear at the upper one fourth part. This type patterns are observed only in crushing failure. The strain in control sample was 0.545 percent.

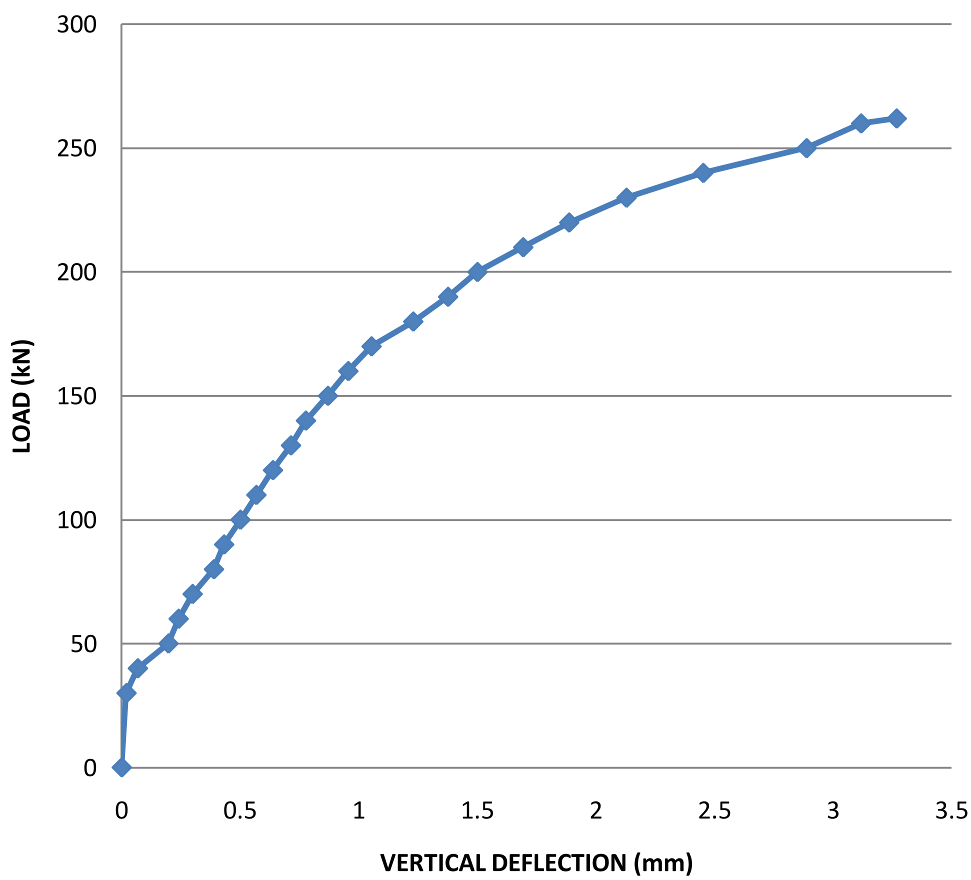


Fig. 4.1 Load vs. Vertical Deflection (CS)

Fig. 4.2 Different Phases of Control Column (CS)

(a) Before loading, (b) After failure, (c) Crack pattern at top

4.2.2 Results of Square Column (Sharp Edges) Confined with Three Layer of GI Wire Mesh (RFCS)

These samples were confined with three layers of GI wire mesh and tested with the same procedure used for control samples. The cross-sectional area of these samples was increased from 100mm X 100mm to 150mm X 150mm, which was due to 25mm thick ferrocement jacketing. As the load applied to the column some continuous cracking sound was heard which may be due to the extension of wire mesh. Some small cracks start appearing on column surface at a load of 210kN. As the loading continued it is observed that the ferrocement jacket fails first with cracks extending from top to mid height. Continuous cracking sound was heard in this case from beginning of the test. The column reaches its ultimate load at 440.2kN. It is observed that the failure of RFCS samples was due to the failure of ferrocement jacket followed by the crushing failure of column, as negligible mid height deflection was observed. The maximum vertical deflection of 3.86mm was observed at ultimate load. Fig. 4.3 shows the load vs. vertical deflection graph. The crack pattern observed after failure is shown in fig. 4.4. It can be observed from the crack pattern that the cracks were extending at corners which may be due to the sharp corners of the specimens or stress concentration at corners of column confined with ferrocament. It is observed that by confining the column with three layers of ferrocement jacketing increases the load carrying capacity by 68.01 percent compared to control sample. The strain of RFCS was also increased from 0.545 percent to 0.643 percent.

It can be observed from literature (Malhotra, 2013) that the confinement of columns with single layer and double layer also increases the load carrying capacity of columns. It is observed from his results that load carrying capacity could be increased to 36.11 percent and 40.07 percent by confining the column with one and two layers of ferrocement jacketing respectively. Whereas in present work confining with three layers of ferrocement jacketing increase the load carrying capacity to 68.01 percent. This result show that three layers of ferrocement jacketing is giving very good strength as campare one layer and two layers ferrocement jacketing.

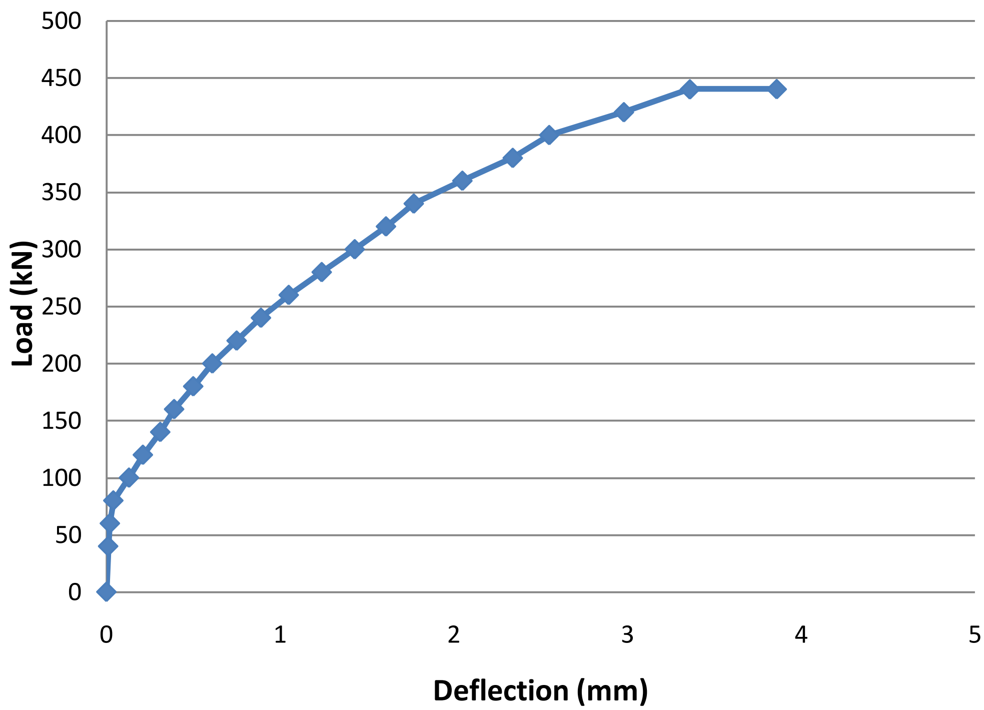


Fig. 4.3 Load Vs. Vertical Deflection (RFCS)

Fig. 4.4 Crack pattern after failure (RFCS)

4.2.3 Results of Square Column (Rounded Edges) Confined with Three Layer of GI Wire Mesh (RFCRC)

To reduce the stress concentration at corners the edges of square samples were made rounded and then confined with three layers of ferrocement jacket. The loading is applied to the samples in the same manner as in case of control sample. As the load applied a cracking sound was heard. At a load of 260kN very small cracks appeared on the specimen. As the loading continued the sound of ferrocement failure is also persistent and the cracks widen with loading. At an ultimate load of 477.6kN the sample fails. Maximum vertical deflection of 4.06mm was observed at failure. It is observed that the confinement was strong as compare to RFCS sample. Fig. 4.5 represents the graph of vertical deflection with respect to load and Fig. 4.6 shows the failure pattern of RFCRC. As there was no significant mid height lateral deflection was observed, the failure occurred due to the failure of wire mesh followed by the crushing failure of column.

There is 82.29 percent increase in ultimate load carrying capacity with respect to control sample was observed. The best results were given by RFCRC samples. The strain is also increased from 0.545 percent to 0.68 percent. The crack patterns after the failure are shown in fig. 4.5. It can be seen that the cracks were extending to the middle instead of extending towards corners. This was due to the reduction of stresses at corners by making them rounded. As the main purpose of making the edges rounded, is to reduce the stresses at corners and it is clear from the failure pattern that the cracks were not extending towards the corners, which shows that the stresses at corners are reduced to a great extent.

4.2.4 Results of Square Column (Sharp Edges) Confined with Single Layer of GI Wire Mesh and Two Extra Layers of GI Wire Mesh at Corners (RFCSC)

RFCSC type specimens were confined with single layer of GI wire mesh and two extra layers of GI wire mesh at each corner. The concept of extra layers of wire mesh at corner was taken to counterbalance the stresses at corners i.e. to restraining the corners. After 28 days of curing period these specimens were tested in compression as done in the last cases.

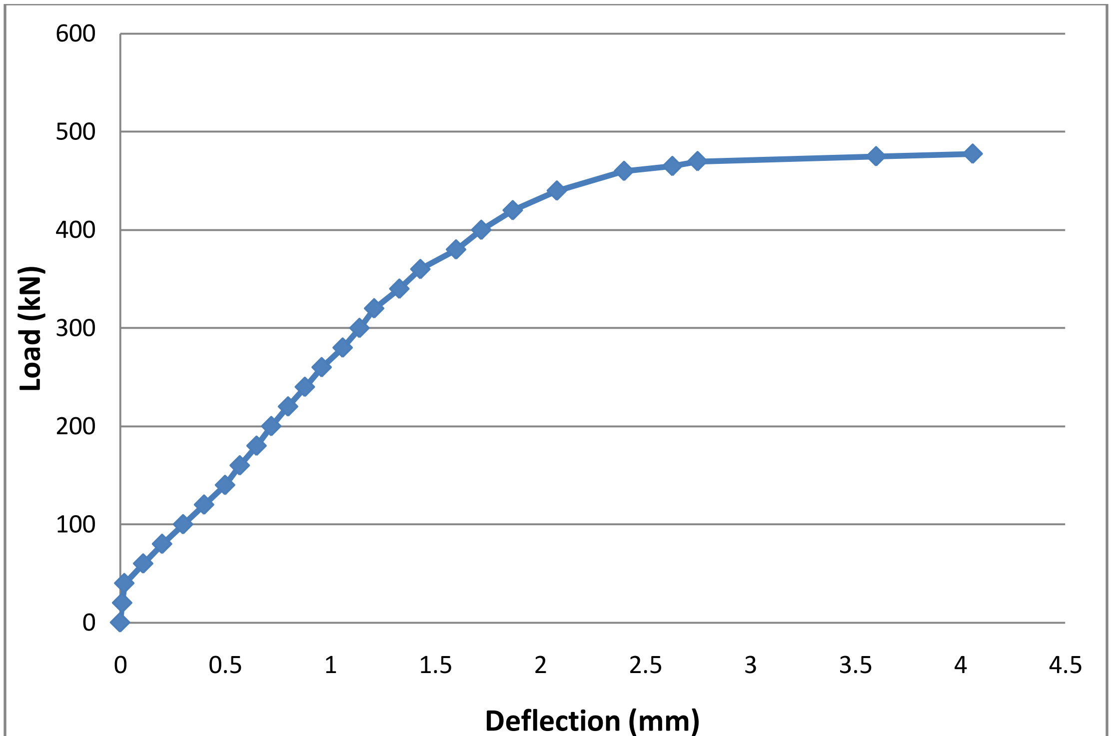


Fig. 4.5 Load Vs. Vertical Deflection (RFCRC)

(a) **(b)**

Fig. 4.6 Failure Pattern of RFCRC

(a) After failure (b) Crack pattern at the Top

As the load is applied some low level cracking sound was heard which might be due to the micro cracks in ferrocement. At a load of 190kN the cracks starts appearing on column surface. After further load application some cracks on ferrocement jacket at top and bottom side faces were observed which shows that ferrocement jacket fails first. At a load of 401.2kN the sample reaches its ultimate load. 53.13 percent increase in load carrying capacity was observed with respect to control sample.

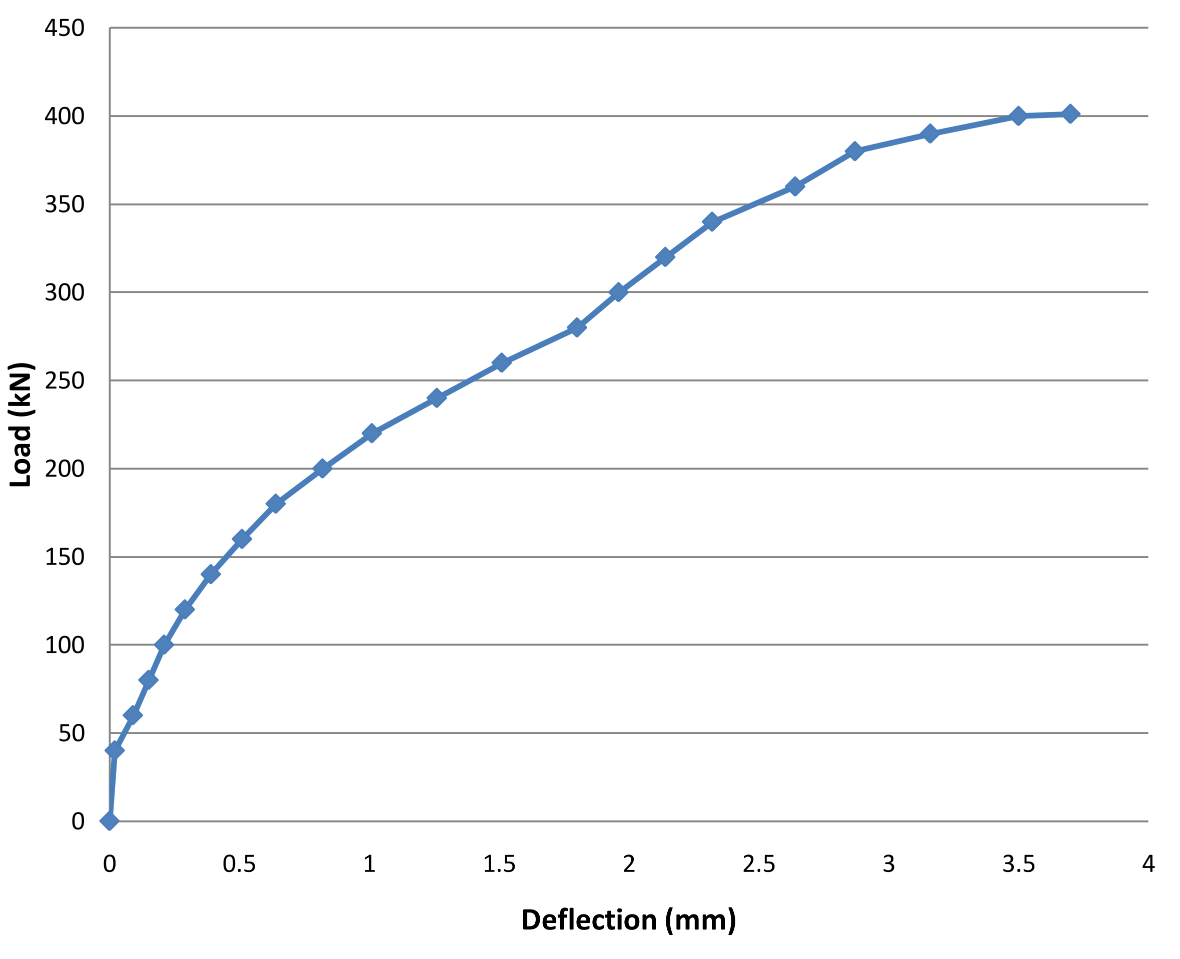
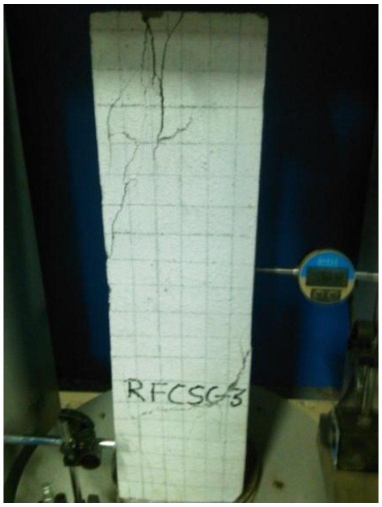
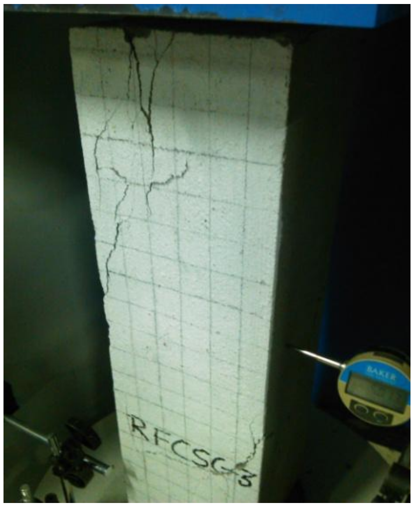


Fig. 4.6 Load Vs. Vertical Deflection (RFCSC)

The test results shows that it is better to confine the samples with this technique as compare to single layer and double layer confinement, but strengthening the corners is a tedious work. Instead of restraining the corners, we can confine the samples with three layers of ferrocement jacketing. We can get good strength by strengthening the column with three layer of ferrocement jacket. The maximum vertical deflection observed in this case was 3.7mm. Fig. 4.6 represents the load vs. vertical deflection graph. Negligible lateral deflection was observed at the mid height which shows that the failure was due to crushing. Strain after failure is increased from 0.545 percent to 0.62 percent. Observed cracks were extending from top and bottom faces to the mid height as shown in fig.4.7. The crack pattern shown in fig 4.7 (d) shows that the cracks are extending from bottom middle face to corner which are due to the restrained corners.



(a)



(b)

(c)

(d)

Fig. 4.7 Different Faces of RFCSC After Failure

4.2.5 Results of Square Column (Rounded Edges) Confined With Single Layer of GI Wire Mesh and Two Extra Layers of GI Wire Mesh at Corners (RFCRCC)

To reduce the stress concentration at corners the corners of square samples were made rounded and then confined with single layer of GI wire mesh and two extra layers of GI wire mesh at corners. After completion of curing period of 28 days the specimens were tested in compression as discussed chapter 3. As the load applied cracking sound was heard. It is observed that at 200kN of load small cracks were appear on the faces of column and at a load of 414.5kN the column reaches to its ultimate load. It is observed that the ferrocement jacket fails first followed by the failure of column. An increase of 58.80 percent in ultimate load carrying capacity was observed, which shows that this technique of ferrocement jacketing is better than RFCSC. Maximum vertical deflection of 3.9mm was observed. The strain is increased to 0.65 percent from 0.54 percent. From the results of all samples it is observed that RFCRC type technique is better than all other techniques. Fig. 4.8 represents the graph between load and vertical deflection.

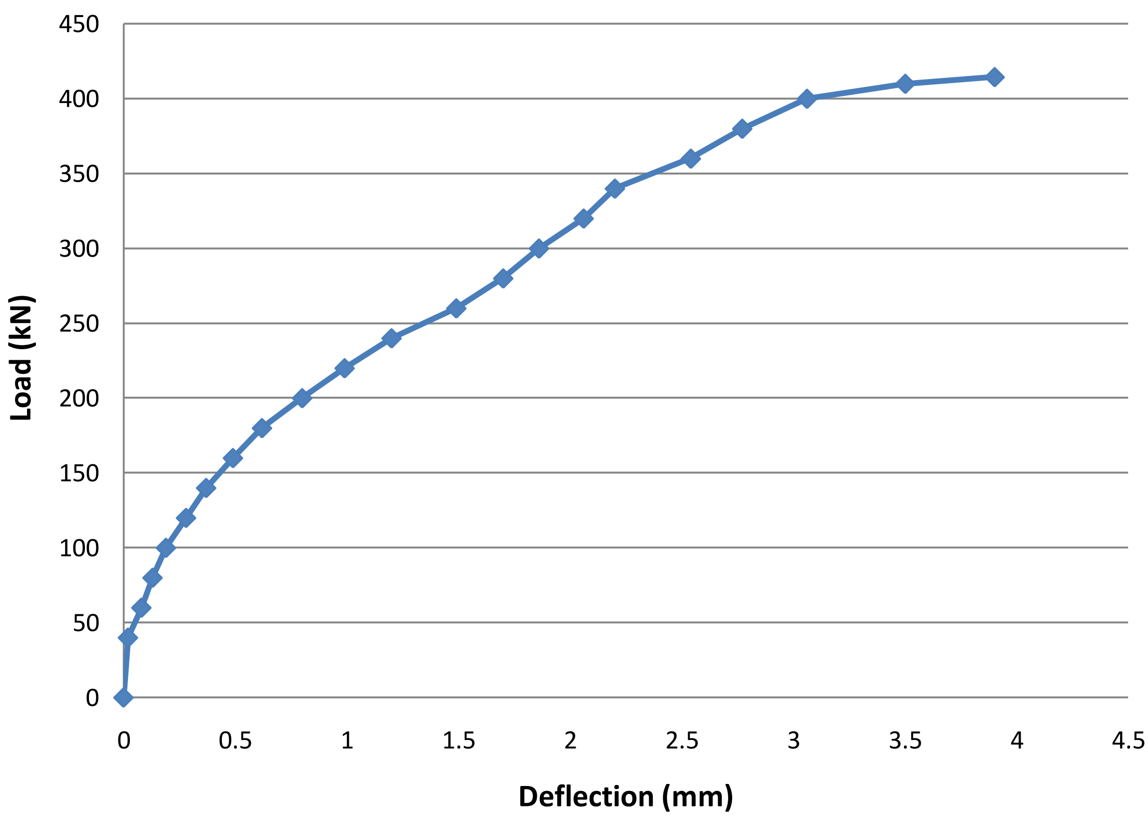


Fig. 4.8 Load Vs. Vertical Deflection (RFCRCC)

The crack patterns observed after the failure are shown in fig. 4.9. It is seen that the cracks start extending from middle of top face to the mid height, which indicates that the stresses at corners are reduced to a significant amount as these columns are confined after making the corners rounded.

(a) (b) (c)

Fig. 4.9 RFCRCC - After failure

4.2.6 Comparison of CS, RFCS, RFCRC, RFCCSC and RFCRCC

(a) Ultimate load carrying capacity

After testing the samples the ultimate load carrying capacity of all samples is compared. Table 4.1 shows the average ultimate load carrying capacity of tested specimens. After getting all test results of confined and unconfined square columns it is found that the load carrying capacity of columns is increased to a great extent after confinement. The ultimate load carrying capacity of confined columns with rounded corners is more than the confined columns with sharp corners. The load carrying capacity of RFCRC is more than the load carrying capacity of RFCS. It is observed that making the corners rounded reduces the stresses at corners and increases the load carrying capacity and ductility after confinement. Similarly the load carrying capacity of RFCRCC column specimens is found more than that of RFCSC. The ultimate load carrying capacity of RFCS, RFCRC, RFCSC, RFCRCC type specimens is increased to 68.01 percent, 82.29 percent, 53.13

percentand 58.20 percent respectively. It is observed that the three layer ferrocement confinement is better than that of corner restrained confinement. Fig 4.10 represents the Graph Showing Comparison of CS, RFCS, RFCRC, RFCSC and RFCRCC.

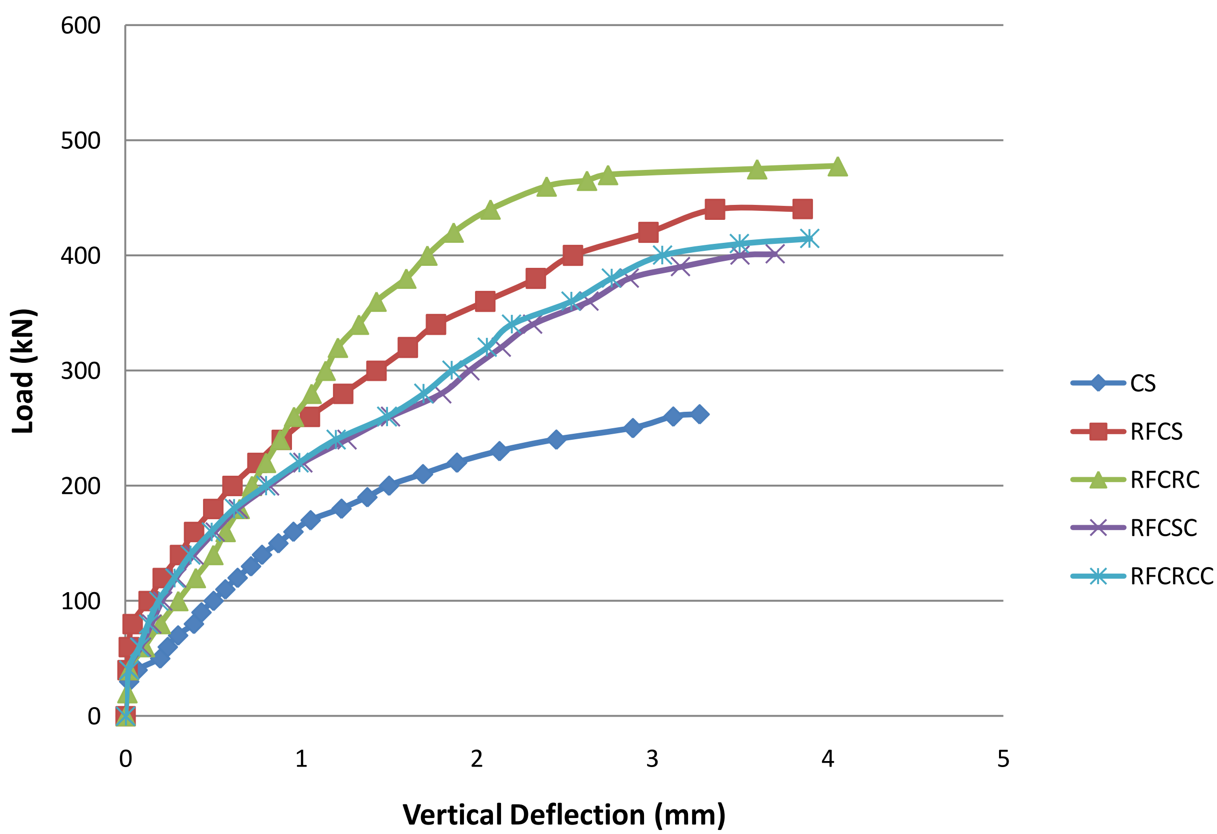


Fig. 4.10 Graph Showing Comparison of RFCS, RFCRC, RFCCSC and RFCRCC

Table 4.1 Average Ultimate Load Carrying Capacity of Tested Specimens

Sr. No.	Specimen type	Ultimate Load (kN)	Increment in ultimate load carrying capacity (%)
1	CS	262	-
2	RFCS	440.2	68.01
3	RFCRC	477.6	82.29
4	RFCSC	401.2	53.13
5	RFCRCC	414.5	58.20

(b) Deflection response

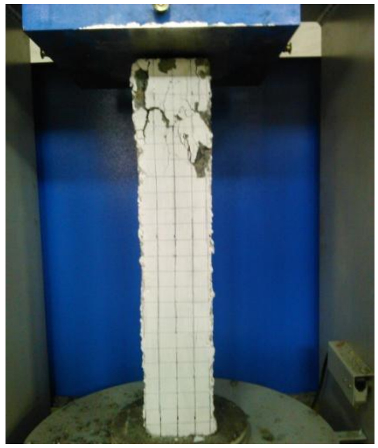
All jacketed specimens show higher ultimate deflection, i.e. axial ductility than the benchmark specimen. Table 4.2 shows the average ultimate vertical deflection of all tested specimens. Lateral deflection at the mid height of all jacketed specimen is also shown in table 4.2. It is clear from the table that type RFCRCC shows highest value of both axial and lateral deflection.

Table 4.2 Average ultimate vertical and lateral deflection of tested specimen

Sr. No.	Specimen type	Ultimate vertical deflection (mm)	Increment in vertical deflection (%)	Ultimate lateral deflection (mm)	Increment in lateral deflection (%)
1	CS	3.27	0	0.324	0
2	RFCS	3.86	18.04	0.830	156.17
3	RFCSC	3.7	11.62	0.521	60.80
4	RFCRC	4.06	24.15	0.681	110.18
5	RFCRCC	3.9	19.26	1.157	257.10

(c) Failure pattern

Typical failure patterns of tested columns are shown in fig. 4.11. It is seen that non jacketed column starts to fail by crushing of concrete. On the other hand, all jacketed columns start to fail from ferrocement jacket. In control sample the cracks start appearing on the column face after the application of load and those cracks widens with respect to load. Some bursting of concrete is also observed. In type RFCS and RFCSC specimens the cracks were seen extending towards corners. In case of type RFCRC and RFCRCC, cracking occurs at middle of corner face extending towards the mid height. Rounding the corner reduces the stress concentration at corners and makes the middle of the face effective.



(a) CS

(a) RFCS

(a) RFCRC

(b) RFCSC

(c) RFCRCC

Fig 4.11 Failure Patterns of Square Confined and Unconfined Specimens

4.3 RESULTS OF CYLINDRICAL COLUMNS

CS 1, CC 1, CC 2, and CC 3 column specimens were tested after a completion of 28 days curing period. The test results of these specimens discussed below.

4.3.1 Result of Control Sample (CS 1)

After the completion of curing period of 28 days all control samples were tested in compression as discussed in test setup in chapter 3. The vertical deflection, lateral deflection and ultimate load at which sample fails was recorded. As the load applied some low level cracking sound was heard. This may be due to the micro cracking of concrete. At a load of 200kN cracks start appearing on column surface. Cracks extend from top to mid height. At a load of 500.4kN the column reaches its ultimate load. The failure of column was due to crushing; as negligible lateral deflection was observe at mid height.

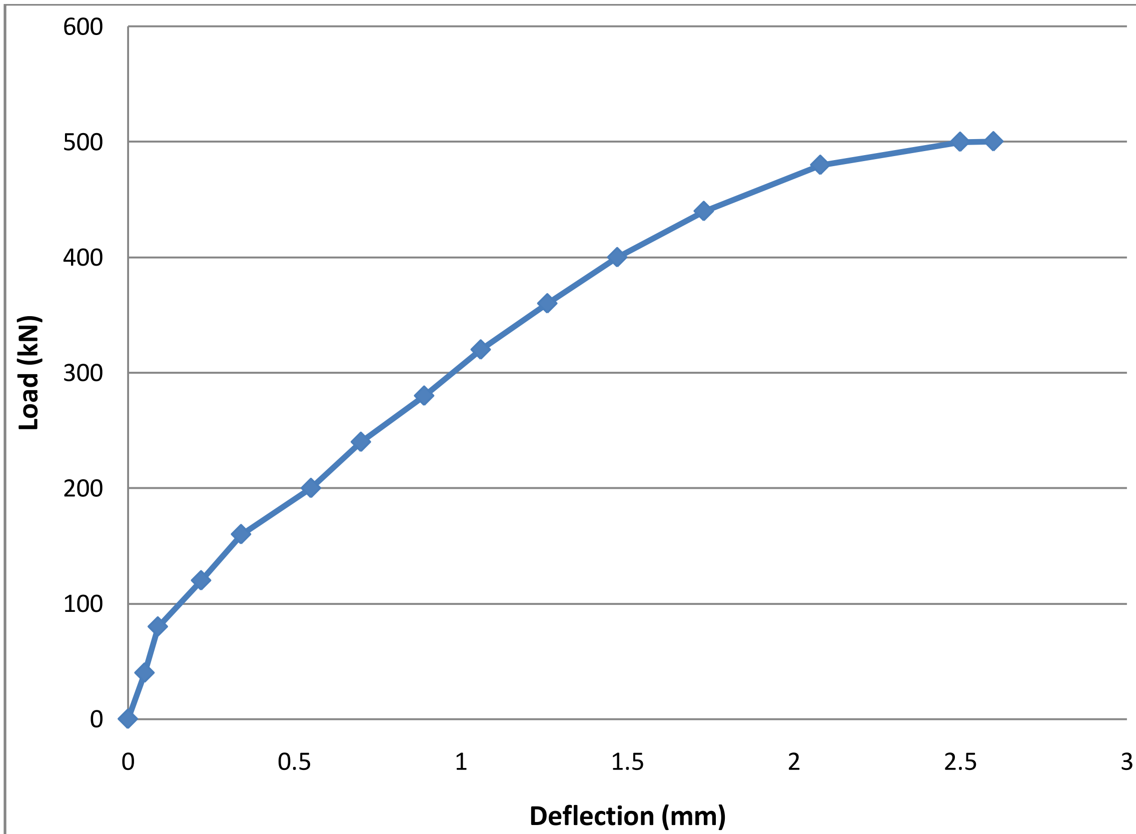


Fig.4.12 Load Vs. Vertical Deflection (CS 1)

Maximum vertical deflection of 2.6mm was observed at ultimate load. Fig. 4.12 represents the load vs. deflection graph. The strain in the control sample after failure was 0.43 percent. The cracks during application of load extend from top to mid height. Fig. 4.13 shows the column before loading and after failure.

(a)

(b)

Fig. 4.13 Different Phases Of Circular Control Column (CS 1)

(a) Before Loading , (b) After Failure

4.3.2 Results of Cylindrical Column Confined with One Layer of GI Wire Mesh (CC 1)

The circular samples after a curing period of 7 days confined with single layer of ferrocement jacket. After confinement the diameter of confined sample was increased to 200mm. Then the confined sample was cured for 28 days and after completion of curing period the sample is tested under compressive loading. When the load is applied to the sample some sound of micro cracks was heard. At a load of 350kN the cracks start appearing on the column face. With the continuation of load the cracking sound of further extension of wire mesh was heard and at an ultimate load of 696.8kN the specimen fails. The failure of column was start with spalling of ferrocement jacket at the bottom followed by the crushing failure of column. By jacketing the column with single layer of wire mesh an increase of 196.4kN was observed with respect to control sample. 39.24 % increase in ultimate load carrying capacity was observed as compare to the control sample. 2.98mm of maximum vertical deflection was observed at ultimate load. Fig. 4.14 shows the load vs. deflection graph. The strain is increased to 0.50% from 0.43% after confining the column with single layer of GI wire mesh. No significant mid height deflection was observed. So the failure was due to the crushing of concrete. Fig. 4.15 shows the sample before loading and after failure.

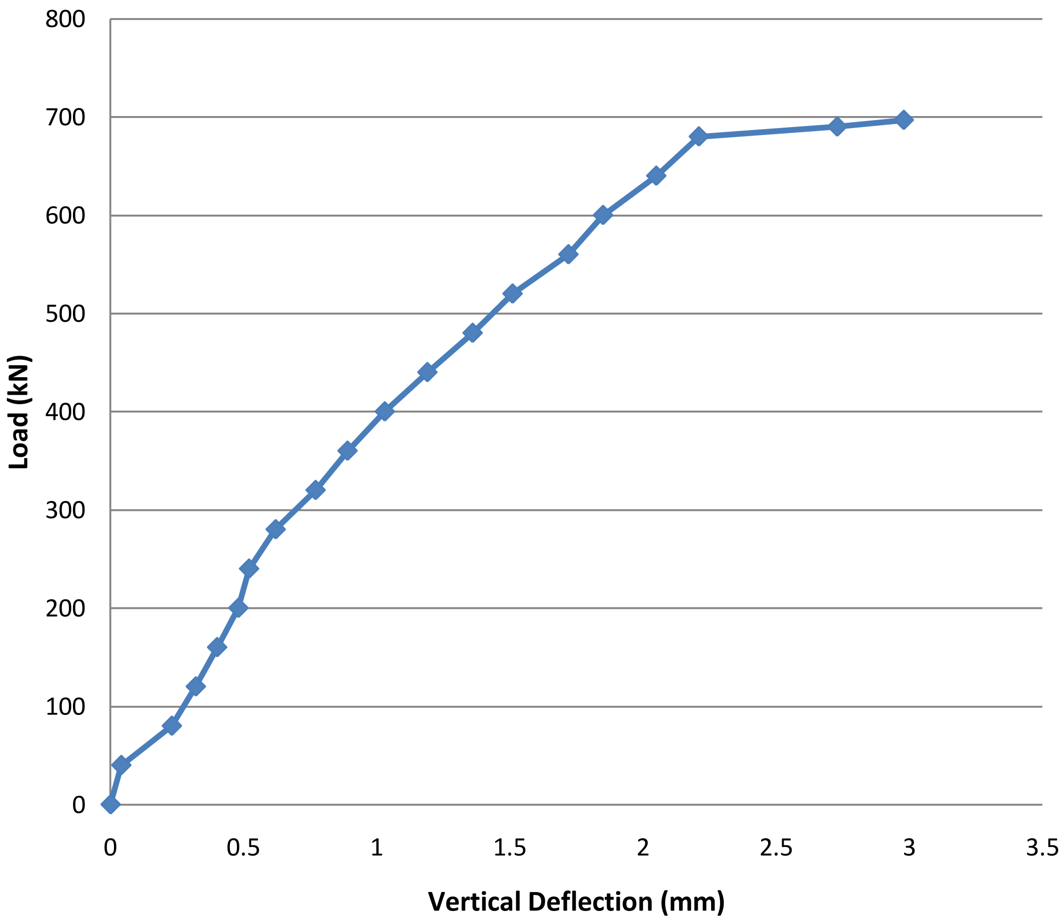


Fig. 4.14 Load Vs. Vertical Deflection (CC 1)

(a) **(b)**

Fig. 4.15 Cylindrical Column – CC 1 before Loading and after Failure
(a) Before loading (b) After Failure

4.3.3 Results of Cylindrical Column Confined with Two Layer of GI Wire Mesh (CC 2)

These samples are confined with two layers of GI wire mesh and left for 28 days of curing period. After completion of curing period the samples were tested under the compressive loading as done for control samples. At the beginning when the load is applied some cracking sound which was due to the extension of wire mesh was heard. This sound is continued up to the failure. The cracks start appearing at a load of 390kN. At an ultimate load of 792.8kN the column specimen fails in compression. The load carrying capacity of this specimen is more than the load carrying capacity of single layer confined sample. Ultimate load carrying capacity is increased to 58.30% compared to control specimen. Vertical deflection of 3.31mm was observed at ultimate load. Fig. 4.16 represents the load vs. deflection graph. The strain was increased to 0.55% from 0.43% after confinement. The cracks observed are shown in Fig 4.17. Spalling of ferrocement jacket is seen during failure. The cracks start from the upper face extending towards the mid height. Confining the column with two layer of GI wire mesh increases the strength up to a significant amount.

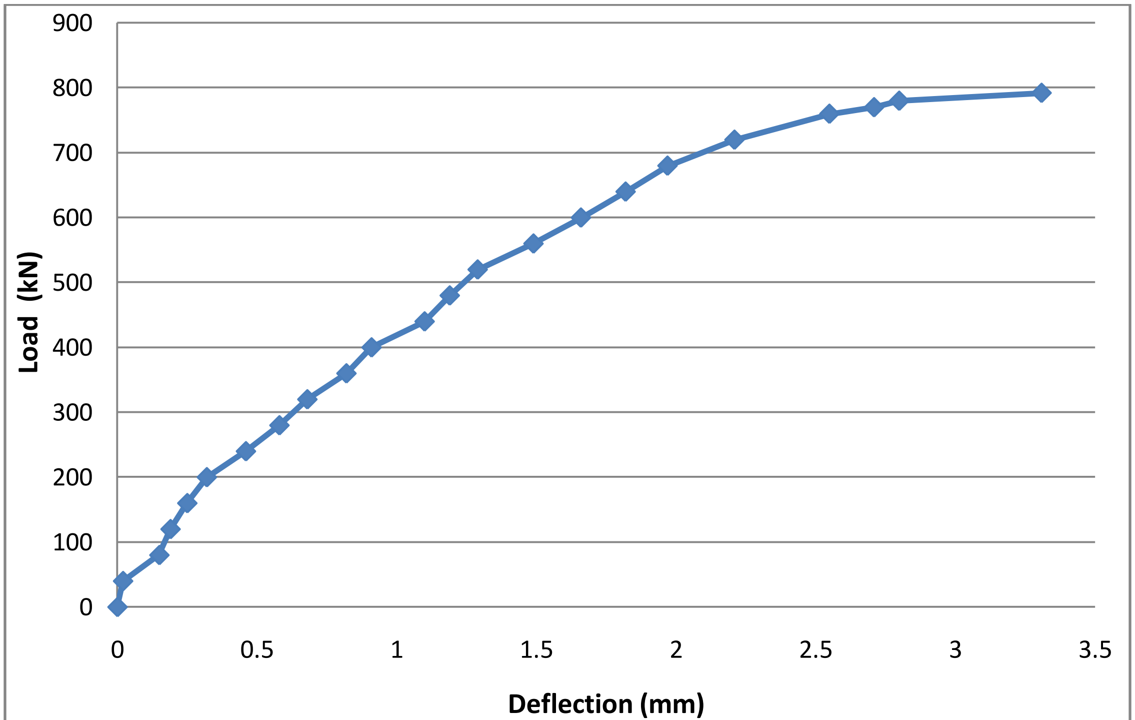


Fig. 4.16 Load Vs. Vertical Deflection (CC 2)

(a) **(b)**

Fig. 4.17 Different Faces Of Two Layer Confined Circular Columns (CC 2) After Failure

4.3.4 Results of Cylindrical Column Confined with Three Layer of GI Wire Mesh (CC 3)

These samples were confined with three layers of GI wire mesh. After completion of curing period the samples were tested as in previous cases. As the load applied very low level cracking sound was heard. Very small cracks start appearing at a load of 400kN. At a load of 620kN extension of cracks is observed. The cracks extend from top to mid height and failure occurred at an ultimate load of 942.2kN. No spalling of mortar like CC 1 and CC 2 was observed. The failure was due to the crushing, as no significant lateral deflection at mid height was observed. 88.29% increase in ultimate load carrying capacity was observed. Vertical deflection of 3.7mm was seen at ultimate load. Fig 4.18 represents the load vs. deflection graph. Strain is increased to 0.62% from 0.43 %. A great increase in ultimate load carrying capacity and strain is observed. Confining the column with three layers of wire mesh is better than CC1, CC2 type. Fig 4.19 shows the failure pattern.

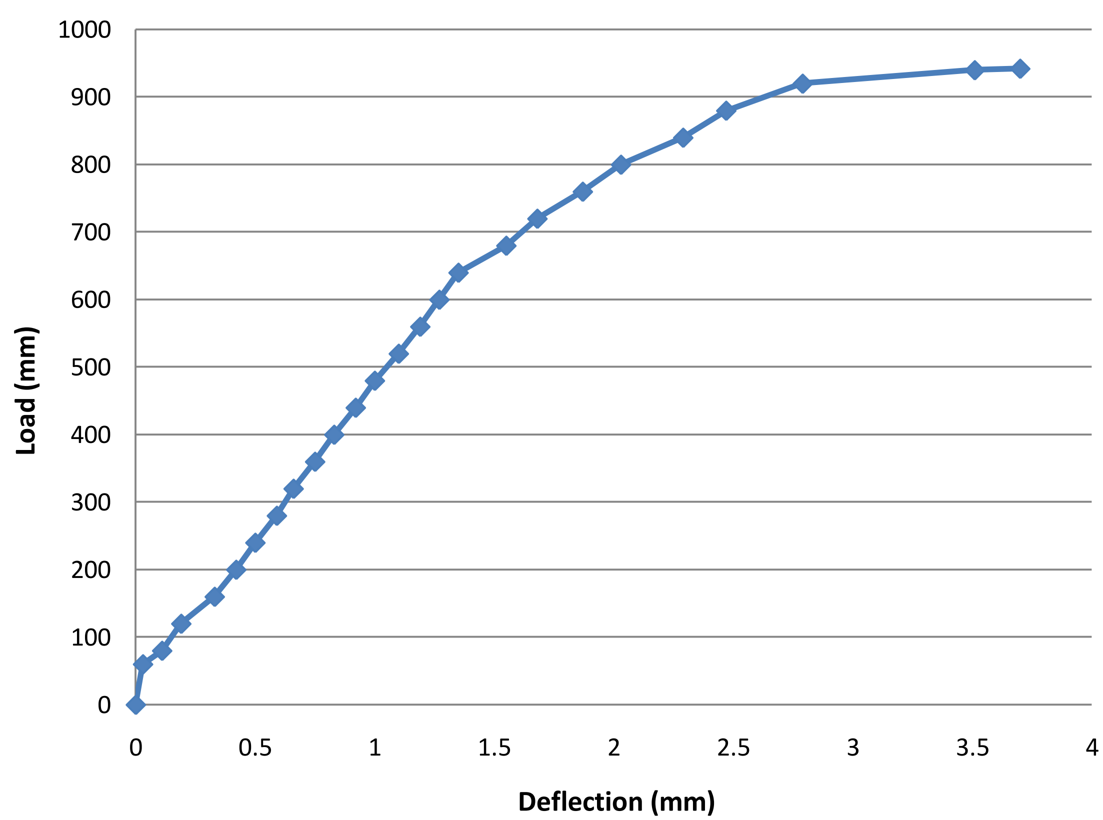


Fig. 4.18 Load Vs. Vertical Deflection (CC 3)

Fig. 4.19 Failure of Circular Column Confined with Three Layers of GI Wire Mesh (CC 3)

4.3.5 Comparison of CS 1, CC1, CC2, CC3

(a) Ultimate Load Carrying Capacity

All ferrocement jacketed specimen shows higher ultimate load carrying capacity than benchmark specimen. Table 4.3 shows the average ultimate load carrying capacity of all tested specimens. CC3 type specimen shows highest load carrying capacity than all type of specimens as it is jacketed with maximum number of wire mesh. Fig. 4.20 shows the graph showing load vs. deflection comparison of jacketed and non jacketed specimens.

(b) Deflection Response

All jacketed specimens show higher ultimate vertical deflection, i.e. axial ductility than bench mark specimen. Table 4.4 shows the average ultimate vertical deflection of all tested specimens. Lateral deflections at mid height of all tested specimens are also shown in table 4.4.

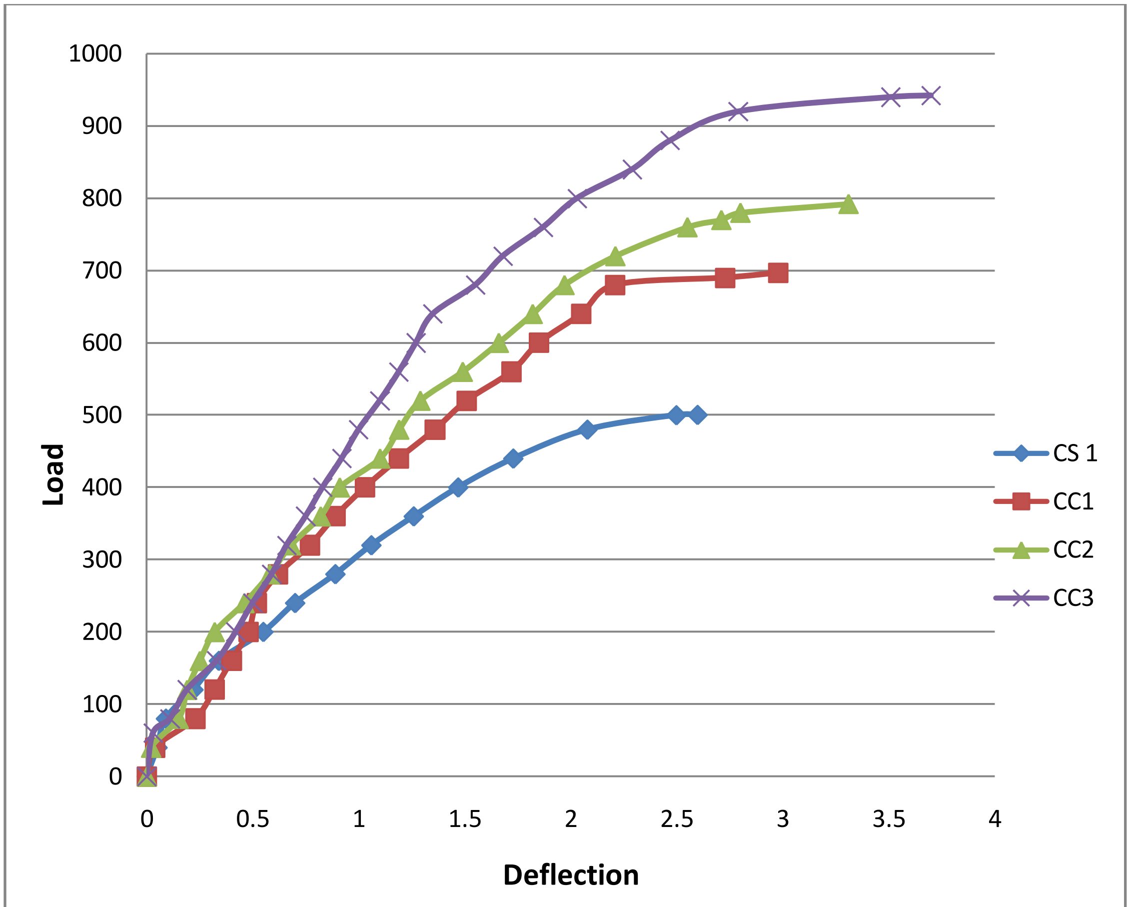


Fig. 4.20 Comparison of CS1, CC1, CC2, CC3

Table 4.3 Average Ultimate Load Carrying Capacity of Tested Specimens

Sr. No.	Specimen type	Ultimate Load (kN)	Increment in ultimate load carrying capacity (%)
1	CS 1	500.4	-
2	CC 1	696.8	39.24
3	CC 2	792.18	58.30
4	CC 3	942.2	88.29

(c) Failure Pattern

Typical failure patterns of all tested columns are shown in fig. 4.21. It is seen that non-jacketed column i.e. control column (CS 1) starts to fail by crushing of concrete. On the other hand, all jacketed column starts to fail from ferrocement jacket. Spalling of mortar in CC1 and CC2 was observed whereas in CC3 no spalling is observed.

Table 4.4 Average Ultimate Vertical and Lateral Deflection of tested Specimens

Sr. No.	Specimen type	Ultimate vertical deflection (mm)	Increment in vertical deflection (%)	Ultimate lateral deflection (mm)	Increment in lateral deflection (%)
1	CS 1	2.6	0	0.486	0
2	CC1	2.98	14.61	0.712	46.50
3	CC2	3.31	27.30	0.844	73.66
4	CC3	3.7	42.31	1.13	132.51

(CS1) (CC1) (CC2) (CC3)

Fig 4.21 Failure Patterns of Cylindrical Specimen

CHAPTER 5
CONCLUSION

From the experimental investigation of ferrocement jacketed RC square and circular columns under concentric load, the following concluding remarks could be made:

- Ferrocement confinement improves the ultimate load carrying capacity of RC column.
- Ferrocement confinement increases the ultimate axial deflection and ductility of RC column.
- Strengthening the square column by making the corners rounded is more effective than strengthening the column by keeping their edges sharp.
- It is concluded that instead of strengthening the corners of columns with single layer and two extra layers at corners by ferrocement jacketing, it is better to round the corners and strengthen the sample with three layers of ferrocement jacketing.
- It is concluded that type RFCRC (column with rounded corners confined with three layer of ferrocement jacketing) and RFCRCC (column with rounded corners confined with single layer of ferrocement jacketing and two extra layers of ferrocement jacketing at corners) type ferrocement jacketing technique is better than RFCS and RFCSC respectively.
- Crack patterns of tested square specimen also confirm that type RFCRC and RFCRCC type is more effective than RFCS and RFCSC respectively.
- It is good to strengthen the circular column with three layers of wire mesh than that of two layers and one layer.
- Crack patterns of tested circular column specimen also confirm that CC3 type of ferrocement jacketing technique is more effective than CC1 and CC2.

REFERENCES

ACI Committee 549-R97: State-of-the-Art Report on Ferrocement, ACI 549-R97, in Manual of Concrete Practice, American Concrete Institute, Farmington Hills, Michigan, 1997, 26 pages.

Desai, J.A. (2011), "Corrosion and Ferrocement, Proceedings of the National Conference on Ferrocement". FS 2011, 13-14 May 2011, Pune, India, pp 45-52.

IS 456-2000: Code of practice- plain and reinforced concrete, Bureau of Indian Standard, New Delhi-2000

Kaish, A. B. M., Alam, M. R., Jamil, M., & Wahed, M. A. (2013). Ferrocement Jacketing for Restrengthening of Square Reinforced Concrete Column under Concentric Compressive Load. *Procedia Engineering*, *54*, 720-728.

Kaish, A. B. M. A., Alam, M. R., Jamil, M., Zain, M. F. M., & Wahed, M. A. (2012). Improved ferrocement jacketing for restrengthening of square RC short column. *Construction and Building Materials*, *36*, 228-237.

Kaish, A. A., Wahed, M., & Alam, M. (2013). Behaviour of ferrocement encased square reinforced concrete column under eccentric loading.

Kondraivendhan, B., & Pradhan, B. (2009). Effect of ferrocement confinement on behavior of concrete. *Construction and Building Materials*, *23*(3), 1218-1222.

Malhotra, J. (2013). Behaviour of rcc columns confined with ferrocement. M.E. Thesis

Mourad, S. M., & Shannag, M. J. (2012). Repair and strengthening of reinforced concrete square columns using ferrocement jackets. *Cement and Concrete Composites*, *34*(2), 288-294.

Naaman, A.E. (2000), "Ferrocement & Laminated Cementitious Composites". Techno Press 3000, Ann Arbor, Michigan, USA, 2000.

Paramasivam, P. (2001). Ferrocement structural applications. *C. Our World In Concrete & Structures. National University of Singapore, Singapore*.

Paramasivam, P., Ong, K. C. G., & Lee, S. L. (1988). *Ferrocement structures and structural elements* (pp. 289-338). Elsevier Applied Science Publishers Ltd.

Sakthivel, P. B., & Jagannathan, A. (2013). Ferrocement construction technology and its applications–A Review.

Shannag, M. J., & Mourad, S. M. (2012). Flowable high strength cementitious matrices for ferrocement applications. *Construction and Building Materials*, *36*, 933-939.

Takiguchi, K. (2003). An investigation into the behavior and strength of reinforced concrete columns strengthened with ferrocement jackets. *Cement and Concrete Composites*, *25*(2), 233-242.

Xiong, G. J., Wu, X. Y., Li, F. F., & Yan, Z. (2011). Load carrying capacity and ductility of circular concrete columns confined by ferrocement including steel bars. *Construction and Building Materials*, *25*(5), 2263-2268.

Yaqub, M., Bailey, C. G., Nedwell, P., Khan, Q. U. Z., & Javed, I. (2013). Strength and stiffness of post-heated columns repaired with ferrocement and fibre reinforced polymer jackets. *Composites Part B: Engineering*, *44*(1), 200-211.