REHABILITATION OF EXTERIOR BEAM COLUMN JOINT USING FIBRE MATS AND GEOPOLYMER CONCRETE

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Abstract

The basic requirement of design is that the joint must be stronger than the adjoining hinging members, usually the beam-column joint. The existing reinforced concrete beam-column joints which are designed as per code IS 456:2000 do not meet the requirements given in the ductility code IS 13920:1993. Hence the beam-column joints that are not designed as per the ductility code may not perform well when subjected to seismic forces. They must be strengthened in order to improve the performance during earthquakes. The technique for strengthening the reinforced concrete structural members is through confinement with wrapping of an external fiber reinforced polymer sheets. The T-beam-column joint specimens as per code IS 456:2000 retrofitted with various fiber reinforced polymer sheets are tested to failure at 60% of the ultimate load. The various types of fiber reinforced polymer sheets used during the present investigation are GFRP and hybrid fiber sheets such as GFRP & CFRP and GFRP & BFRP. The T-beam-column joint specimens are caste with the geopolymer concrete. Industrialization leads to the generation and release of undesirable pollutants into the environment. In order to keep pace with the rapid industrialization, there is a necessity to select an engineering process, which would cause minimum pollution into environment. Consequently, in the last two decades, the expansion of this concept and the increasing global warming have raised concerns on the extensive use of Portland cement due to the high amount of carbon dioxide associated with its production. The development of Geopolymer Concretes offers promising signs for a change in the way of producing concrete. However, to seriously consider Geopolymer binders as an alternative to ordinary Portland cement. The selection of suitable ingredients of geopolymer concrete to achieve desire strength at required workability and experimental investigation consists of testing of retrofitted T-beam-column joint specimens under reversal load will be carry out.

I. INTRODUCTION

1. GENERAL

In recent years, the construction industry has seen an increasing demand to reinstate, rejuvenate, strengthen and upgrade existing concrete structures. This may be attributed to various causes such as environment degradation, design inadequacies, poor construction practices, lack of regular maintenance, revision of codes of practice, increase in loads and seismic conditions etc. In India, most of the reinforced concrete structures are designed for gravity loading as per IS 456:2000.During a severe earthquake, the structure is likely to undergo inelastic deformation and has to depend on ductility and energy dissipation capacity to avoid collapse. The beam column joints are susceptible for damage during earthquake. So the performance of beam column joints recognized as a significant factor that affects the overall behavior of reinforced concrete(RC) framed structures subjected to large lateral loads. Jacketing and geopolymer concrete techniques are used to strengthen exterior beam-column joint using fiber mats. Axial strength, bending strength and stiffness of the original beam column joints are increased for the retrofitted beam column joints.

2. RETROFITTING

In recent years, repair and seismic retrofit of concrete structures with FRP sheets has become more common. The strengthening of beam column joint with wrapped FRP sheets to improve seismic performance is one of the major applications of this new strengthening method. The wrapped FRP sheet around the plastic hinge region of beam column joint provides not only enough shear strength but also confinement of concrete to increase the ductility of the beam column joint .Since the total cost of replacement of the vulnerable structures is so overwhelming, the development of innovative rehabilitation and strengthening techniques is required to extend the life expectancy of many existing buildings. Figure 1 shows a reinforced concrete structure that collapsed during the 1999 Kocaeli earthquake in Turkey in which failure of joints appears to be the major contributor to such collapse. Figure 2 shows a typical view of beam-column joint failure.

Figure 1 Collapsed Reinforced Concrete Structure during Kocaeli Earthquake (Reference: www.thecivilbuilders.com)

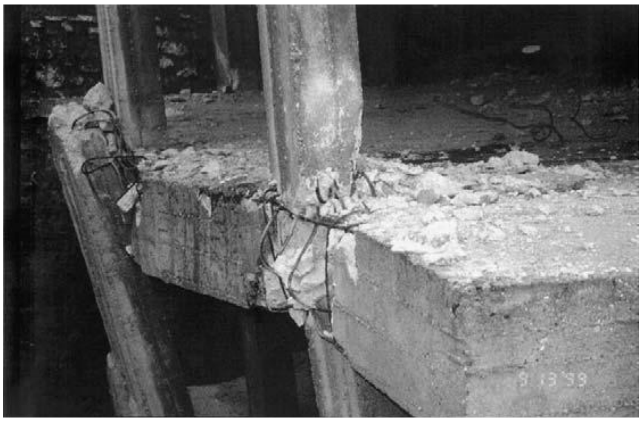

Figure 2 Typical View of Beam-Column Joint Failure (Reference: www.researchgate.net)

3. GEOPOLYMER CONCRETE

Use of concrete is globally accepted due to ease in operation, mechanical properties and low cost of production as compared to other construction materials. An important ingredient in the conventional concrete is the Portland cement. Production of Portland cement is increasing due to the increasing demand of construction industries. Therefore the rate of production of carbon dioxide released to the atmosphere during the production of Portland cement is also increasing. Generally for each ton of Portland cement production, releases a ton of carbon dioxide in the atmosphere. The greenhouse gas emission from the production of Portland cement is about 1.35 billion tons annually, which is about 7 % of the total greenhouse gas emissions. Moreover, cement production also consumes significant amount of natural resources. Therefore to reduce the pollution, it is necessary to reduce or replace the cement from concrete by other cementitious materials like fly ash, blast furnace slag, rice husk ash, etc.

Fly ash is a by-product of pulverized coal blown into a fire furnace of an electricity generating thermal power plant. In India more than 220 million tons of Fly ash is produced annually. Out of this, only 35–50 % fly ash is utilized either in the production of Portland pozzolana cement, workability improving admixture in concrete or in stabilization of soil. Most of the fly ash is disposed off as a waste material that covers several hectares of valuable land. The importance of using fly ash as a cement replacing material is beyond doubt. The replacing cement by fly ash up to 60 % known as high volume fly ash concrete. But it was observed that the pozzolanic action of fly ash with calcium hydroxide formed during the hydration of cement is very slow. The particles of size less than 45 μm are responsible for pozzolanic reaction. Higher size particles present in fly ash acts as filler. Therefore for complete replacement of cement by fly ash and to achieve the higher strength within a short period of curing, Davodavits suggested the activation process of pozzolanic material that are rich in silica and alumina like fly ash with alkaline elements at certain elevated temperature. Fly ash when comes in contact with highly alkaline solutions forms inorganic alumino–silicate polymer product yielding polymeric Si–O–Al–O bonds known as Geopolymer.

Rangan have proposed the mix design procedure for production of fly ash based geopolymer concrete whereas Anuradha et al. have presented modified guidelines for mix design of geopolymer concrete using Indian standard code.

4. SCOPE AND OBJECTIVES

- To produce Geopolymer concrete mixtures with target compressive strength for the manufacture of T-beam-columns joint.
- To carry out an experimental investigation under reversal load to find the load carrying capacity and energy absorption capacity of geopolymer reinforced concrete beam-column joint specimens that are detailed as per code IS 456 : 2000 and retrofitted with glass & hybrid fiber reinforced polymer sheets such as GFRP & CFRP and GFRP & BFRP.
- To perform calculation on load carrying capacity of T-beam-columns joint by Geopolymer concrete.
- To understand the effectiveness of glass and hybrid fiber reinforced polymer sheets in increasing the

load carrying capacity of the beam-column joints.

- To understand the improvement in the ductility as well as result in large energy absorption capacity of retrofitted T-beam-column joints.
- To perform cost analysis to ascertain the affordability of this alumino-silicate concrete.

II. LITERATURE REVIEW

1. REVIEWS OF LITERATURE

Ze-Jun Geng et al (1998) carried out an investigation on the ductility of concrete column-to-beam connection and the capability of connections containing insufficient development length. CFRP sheets were wrapped around the column near the joint region. Repeated loading-unloading-reloading were done on the specimens for simulating seismic loads. Nineteen concrete column-to-beam connection specimens were tested and it was reported that significant improvement in ductility was noticed and the ultimate loading capacity increased in the range from 24% to 35%.

Jianchun Li et al (1999) reported the results of tests on prototype reinforced concrete frame specimens which were designed to represent the column-beam connections in plane frames. The tests were devised to investigate the influence of fiber reinforcement applied to the external surfaces adjacent to the beam-column connection on the behavior of the test specimens under static loading to find the influence of reinforcement on the strength and stiffness. The hybrid FRP composites of glass and carbon with a vinyl-ester resin were designed to externally reinforce the joint of the concrete frame. The results indicated that retrofitting the critical sections of concrete frames with FRP reinforcement can provide strengthening and stiffening to concrete frames and improve their behavior.

Ahmed Khalifa and Antonio Nanni (2000) carried out an investigation on the shear performance of reinforced concrete beams with T-section. Different configurations of externally bonded carbon fiber-reinforced polymer sheets were used to strengthen the specimens in shear. The experimental program consisted of six full-scale, simply supported beams. One beam was used as a bench mark and five beams were strengthened using different configurations of CFRP. The experimental results indicated that externally bonded CFRP can increase the shear capacity of the beam significantly.

Andrea Prota et al (2004) presented the key issue of strengthening of RC frames by the strengthening of beam-column connection. For upgrading the beam-column joint, the proposed technique was based on the combined use of externally bonded FRP laminates and Near Surface Mounted (NSM) FRP bars. The results of the experimental investigation indicated that FRP laminates which were used in joint region improved the shear capacity. It is reported that the NSM bars improved the flexural capacity. The experimental results indicated that the strength of control specimens increased by 39 %. with some modifications. With the generic information available on Geopolymers, a rigorous trial-and-error method was adopted to develop a process for manufacturing fly ash-based Geopolymer concrete following the technology currently used to manufacture Ordinary Portland Cement concrete. In addition, the price of fly ash-based Geopolymer concrete is estimated to be about 10% to 30% cheaper than that of Portland cement concrete. Also, due to the presence of sodium silicate, a sticky gel in nature, and fly ash, a finer element, it was recommended to increase the quantity of sodium silicate and fly ash by 20% than the quantity obtained by Mix Design.

Sumajouw et al (2006) have conducted experimental and analytical studies to establish the behaviour and strength of reinforced Geopolymer concrete slender columns subjected to axial load and bending moment. The correlation of experimental results with prediction methods currently used for reinforced Portland cement concrete structural members was also done and presented. All columns were 175mm square and 1500mm in length. Six columns contained four 12mm deformed bars, and the other six were reinforced with eight 12mm deformed bars as longitudinal reinforcement. Thus the reinforcement ratio was 1.47% and 2.95% respectively. A concrete cover of 15mm was provided between the longitudinal bars and all faces of the column. Due to the use of end assemblages at both ends of test columns, the effective length of the columns measured from centre-to-centre of the load knife edges was 1684mm. All the columns were cured at a temperature of 60°C for 24 hours. All columns were tested in a Universal test machine of capacity 2500kN.

2. RESEARCH SIGNIFICANCE

Based on the review of literature, it is found that only very few experimental investigations of T-beam-column joints were carried out to study the behavior of the reinforced geopolymer concrete T-beam-column joint specimens retrofitted with FRP sheets. Also it is found that comparison of performance of different types of fiber reinforced polymer sheets has not been done. Hence an attempt has been made to carry out an investigation to understand the behavior of the reinforced concrete T-beam-column joint specimens retrofitted with GFRP & Hybrid wrapping sheets using geopolymer concrete. Over the last two decades, vast advancement has been made in this alkali-activated Geopolymer technology and more researches have been conducted on the chemical and microstructural aspects of Geopolymers. However, little effort has been put on to find out mechanical aspects of Geopolymers. It is observed from the literature tour that Geopolymer concrete has many positive aspects over ordinary Portland cement concrete and hence the synthesis of Geopolymer matrixes from coal fly ash has been studied experimentally in this research work. Moreover, it is obvious from the available literature, no such work has been experimented on Indian fly ash. The suitability of design provisions contained in the current standards and IS codes for cement concrete are checked in the design of reinforced Geopolymer T-beam column joint.

III. DESIGN REQUIREMENTS OF BEAM-COLUMN JOINT

The basic requirement of design is that the joint must be stronger than the adjoining hinging members, usually the beams or columns. It is important to see that the joint size is adequate early in the design phase, otherwise the size of column or beam may need to be changed to satisfy the joint strength or anchorage requirements. The design of beam-column joints is predominantly focused on providing shear strength and adequate anchorage within the joint. In a global sense, the design procedure of beam-column joints consists of the following steps:

- Determination of the preliminary size for members based on requirements for the chosen longitudinal bars.
- Provision of adequate flexural strength of columns to get the desired beam yielding mechanism.
- Estimation of the design shear force for the joint by evaluating the flexural strength of the adjacent beams and corresponding internal forces. The simultaneous forces in the columns that maintain joint equilibrium must also be determined. From these, the joint shear force can be calculated.
- Estimation of effective joint shear area from the dimension of the adjoining members.
- Maintaining the value of the induced shear stress lower than the allowable stress.
- Provision of transverse reinforcements to confine the concrete and to take shear force.
- Provision of sufficient anchorage for the reinforcement passing through or terminating in the joint.

IV. EXPERIMENTAL INVESTIGATION

1. MATERIALS USED

In the proposed mix proportioning method, low calcium processed fly ash of thermal power plant was used as source material. The laboratory grade sodium hydroxide in flake form (97.8 % purity) and sodium silicate (50.72 % solids) solutions are taken as alkaline activators. Locally available river sand is used as fine aggregate and locally available crushed basalt stones are taken as coarse aggregates.

For the development of fly ash based geopolymer concrete mix design method, detailed investigations have been carried out and following parameters were selected on the basis of workability and compressive strength.

A. Fly ash

Quantity and fineness of fly ash plays an important role in the activation process of geopolymer. It was already pointed out that the strength of geopolymer concrete increases with increase in quantity and fineness of fly ash. Similarly higher fineness shows higher workability and strength with early duration of heating. So, the main emphasis is given on quantity and fineness of fly ash in the development of mix proportioning procedure of geopolymer concrete. So,in the proposed mix design procedure, quantity of fly ash is selected from Fig. 3 on the basis of fineness of fly ash and target strength.

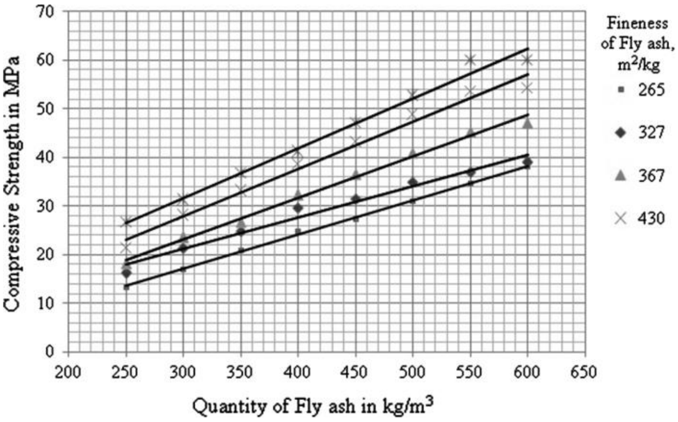

Fig. 3 Effect of quantity of fly ash on compressive strength for different fineness at solution-to-fly ash ratio

B. Alkaline Activators

In the present investigation, sodium based alkaline activators are used. Single activator either sodium hydroxide or sodium silicate alone is not much effective. So, the combination of sodium hydroxide and sodium silicate solutions are used for the activation of fly ash based geopolymer concrete. It is observed that the compressive strength of geopolymer concrete increases with increase in concentration of sodium hydroxide solution and or sodium silicate solution with increased viscosity of fresh mix. Due to increase in concentration of sodium hydroxide solution in terms of molarity (M) makes the concrete more brittle with increased compressive strength. Secondly, the cost of sodium hydroxide solid is high and preparation is very caustic. Similarly to achieve desired degree of workability, extra water is required which ultimately reduce the concentration of sodium hydroxide solution. So, the concentration of sodium hydroxide was maintained at 13 M while concentration of sodium silicate solution.

Figure 4 Sodium hydroxide flakes

Figure 5 Sodium silicate solution

C. Water

From the chemical reaction, it was observe that the water comes out from the mix during the polymerization process. The role of water in the geopolymer mix is to make workable concrete in plastic state and do not contribute towards the strength in hardened state. Similarly the demand of water increases with increase in fineness of source material for same degree of workability. So, the minimum quantity of water required to achieve desired workability is selected on the basis of degree of workability, fineness of fly ash and grading of fine aggregate.

D. Aggregates

Aggregates are inert mineral material used as filler in concrete which occupies 70–85% volume. So, in the preparation of geopolymer concrete, fine and coarse aggregates are mixed in such a way that it gives least voids in the concrete mass. This was done by grading of fine aggregate and selecting suitable fine-to-total aggregate ratio. Workability of geopolymer concrete is also affected by grading of fine aggregate similar to cement concrete.

E. Water-to-geopolymer binder ratio

The ratio of total water (i.e. water present in solution and extra water if required) to material involve in polymerization process (i.e. fly ash and sodium silicate and sodium hydroxide solutions) plays an important role in the activation process. Rangan suggested the water-to-geopolymer solid ratio in which only solid content in solution and fly ash is considered. But the calculation is tedious and water present in solution indicates the concentration of solution itself. So, in the present investigation, water-to-geopolymer binder ratio is considered. From the investigation, it is observed that the compressive strength reduces with increase in water-to-geopolymer binder ratio similar to water-to-cement ratio in cement concrete. At water-to-geopolymer binder ratio of 0.25, the mix was very stiff and at 0.40, the mix was segregated. Similarly water come out during polymerisation process and does not contribute anything to the strength. So, water-to-geopolymer binder ratio is maintained at 0.35 which gives better results of workability and compressive strength.

F. Solution to fly ash ratio

As solution (i.e. sodium silicate + sodium hydroxide) to fly ash ratio increases, strength is also increases. But the rate of gain of strength is not much significant beyond solution to fly ash ratio of 0.35. Similarly the mix was more and more viscous with higher ratios and unit cost is also increases. So, in the present mix design method, solution-to-fly ash ratio was maintained at 0.35.

2. MIX DESIGN FOR M_{30} CONCRETE

Table 1 Materials required for M30 grade geopolymer concrete

Ingredients of geopolymer concrete	Fly ash	NaOH	Na_2SiO_3	Sand	Coarse aggregate	Total water
Quantity (kg/m^3)	394	68.95	68.95	554	1294	110

V. TESTING OF SPECIMENS:

1. Testing of cubes and cylinders:

(a)Compressive Strength Test:

Geopolymer concrete cubes of size 150mm × 150mm × 150mm were cast and tested in accordance with IS: 516-1959. Alkaline solution used was silicates and hydroxides of sodium. Geopolymer concrete cubes were manufactured and tested. Three numbers of specimens were cast and tested in a hydraulic compression testing machine of capacity 2000kN. Table 2 shows the various compressive strength of cubes.

Table 2 Compressive Strength of Concrete Cubes

Mix identity	Concentration of NaOH in Molars	Age of concrete in days	Mean compressive strength in N/mm^2
G30	13M	7	15.33
		14	19.33
		28	28.45

(b) Split Tensile Test:

For the mixture of G30 concrete, three specimens of 150mm × 300mm size cylinders for each mixture were cast and split tensile strength test was carried out in accordance with IS:5816-1999. Geopolymer concrete specimens were tested. Surface water was wiped off the concrete specimens before testing. Central lines were drawn on the opposite faces of the cylinders to ensure that they were in the same axial plane. Specimens were placed in the Compression Testing Machine and packing strips were placed at the point of contact of load. Packing strips made of hardboard were carefully positioned in parallel to the top and bottom plane of loading. The load was applied smoothly and continuously at nominal rate until failure. The diametrical compressive load along the height of the cylinder was applied and the ultimate load at failure or rupture was noted for calculation. The maximum load when divided by the appropriate geometrical factors gave the split tensile strength of the specimen of concrete. Table 3 shows the split tensile strength of the concrete cubes.

Table 3 Spilt Tensile Strength of concrete cylinders

Nomenclature of specimen	No. of Cylinders Tested	Ultimate load in kN	Split tensile Strength in N/mm2	Average Split tensile Strength in N/mm2
G30(13M NaOH)	3	263.68	3.73	3.18
		289.71	4.09	
		273.68	3.87	

2. Testing of Beam-column joint specimens:

(a) Description of the Test Programme

The beam column joint specimens were tested in a loading frame with the column in the horizontal plane. Both the ends of the column were hinged using roller plates. The axial load was applied at one end the column using a hydraulic jack of 500 kN capacity and the load was measured using calibrated dial gauge. The other end of the column was supported by the steel bulkhead attached to the loading frame. A transverse static or push & pull load was applied at the free end of the beam through a push and pull hydraulic jack of capacity 400 kN to develop a bending moment at the joint. The deflection at the free end of the beam was recorded at regular load intervals upto a control deflection. The number of beam-column joint specimens tested during this investigation is 6. Figure 6 shows the typical view of test setup for the beam-column joint specimen.

Figure 6 Typical View of Test Setup

The load reversal (push and pull) tests was carried out on beam-column joint specimens. It is reported in the literature that when the axial load on the column exceeds 50 to 60% of its capacity, the effect of axial load will be more predominant on the joint. But in the case of the seismic forces, the effect of lateral load will be more predominant. Hence in order to truly reflect the performance of the joint under seismic load conditions, it was decided to restrict the axial loads of column is less than 50 % of load carrying capacity of the column. The experimental investigation consisted of applying axial load of 15 % of load carrying capacity of the column and applying a point load at the free end of the cantilever beam portion till the failure of the specimen. The loading was continued till the joint failed by crushing of concrete in the case of control specimens and rupture of wrap in the case of retrofitted specimens. The details of the specimens such as specimen identification number (ID), grade of concrete, axial load on column, type of loading and fiber reinforced polymer sheet used for retrofitting are given in Table 4.

Table 4 Details of the Specimens

Specimen ID	Detailing as per code	Grade of concrete	Type of load	Retrofitted by
BCJ 1	IS 456:2000	G 30	Load Reversal	Nil
BCJ 2	IS 456:2000	G 30	Load Reversal	GFRP
BCJ 3	IS 456:2000	G 30	Load Reversal	CFRP
BCJ 4	IS 456:2000	G 30	Load Reversal	Sisal
BCJ 5	IS 456:2000	G 30	Load Reversal	GFRP-CFRP Hybrid
BCJ 6	IS 456:2000	G 30	Load Reversal	GFRP-CFRP Hybrid

Fig. 7, Fig. 8 , Fig. 9 , & Fig. 10 show the typical views failed control and retrofitted specimens

Figure 7 Typical View of Failed Control Specimen

Figure 8 Typical View of Failed Specimen Retrofitted with GFRP Sheets

Figure 9 Typical View of Failed Specimen Retrofitted with Sisal Fiber Sheet

Figure 10 Typical View of Failed Specimen Retrofitted with CFRP Sheet

(b) Results of Reversal Load test

(i) Beam-Column Joint Specimen 1 (BCJ 1)

Specimen BCJ 1 has been detailed as per code IS 456:2000. An axial load of 65 kN which is 15% of load carrying capacity of column (440 kN) was applied on the column and load at the free end of the beam was gradually increased. During pulling, first crack was formed in the beam portion approximately at a distance of 45 mm from the face of the column at a load of 16 kN. At a load of 17 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 18 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 20 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 22 kN. During pushing, first crack was formed in the beam portion at a load of 14 kN. At a load of 15 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 16 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 18.5 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 20 kN.

(ii) Beam-Column Joint Specimen 2 (BCJ 2)

Specimen BCJ 2 has been detailed as per code IS 456:2000 and was retrofitted with glass fiber reinforced polymer sheets. An axial load of 65 kN which is 15% of load carrying capacity of column (440 kN) was applied on the column and load was gradually increased at the free end of the beam. During pulling, first crack was formed in the beam portion approximately at a distance of 55 mm from the face of the column at a load of 20 kN. At a load of 22 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 24 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 26 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 28 kN. During pushing, first crack was formed in the beam portion at a load of 20 kN. At a load of 21 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 22 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 24 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 26 kN.

(iii) Beam-Column Joint Specimen 3 (BCJ 3)

Specimen BCJ 3has been detailed as per code IS 456:2000 and was retrofitted with carbon fiber reinforced polymer sheets. An axial load of 65 kN which is 15% of load carrying capacity of column (440 kN) was applied on the column and load was gradually increased at the free end of the beam. During pulling, first crack was formed in the beam portion approximately at a distance of 70 mm from the face of the column at a load of 24 kN. At a load of 26 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 28 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 30 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 32 kN. During pushing, first crack was formed in the beam portion at a load of 22 kN. At a load of 24 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 26 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 28 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 30 kN.

(iv) Beam-Column Joint Specimen 4 (BCJ 4)

Specimen BCJ 4 has been detailed as per code IS 456:2000 and was retrofitted with sisal fiber sheets. An axial load of 65 kN which is 15% of load carrying capacity of column (440 kN) was applied on the column and load was gradually increased at the free end of the beam. During pulling, first crack was formed in the beam portion approximately at a distance of 60 mm from the face of the column at a load of 22 kN. At a load of 24 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of

24 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 26 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 27.5 kN. During pushing, first crack was formed in the beam portion at a load of 20 kN. At a load of 21 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 23 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 24 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 25.5 kN.

(v) Beam-Column Joint Specimen 5 (BCJ 5)

Specimen BCJ 5 has been detailed as per code IS 456:2000 and was retrofitted with glass-carbon hybrid fiber reinforced polymer sheets. An axial load of 65 kN which is 15% of load carrying capacity of column (440 kN) was applied on the column and load was gradually increased at the free end of the beam. During pulling, first crack was formed in the beam portion approximately at a distance of 60 mm from the face of the column at a load of 22 kN. At a load of 24 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 26 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 29 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 30 kN. During pushing, first crack was formed in the beam portion at a load of 21 kN. At a load of 22 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 24 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 27 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 28 kN.

(vi) Beam-Column Joint Specimen 6 (BCJ 6)

Specimen BCJ 128 has been detailed as per code IS 456:2000 and was retrofitted with glass-carbon hybrid fiber reinforced polymer sheets. An axial load of 130 kN which is 30 % of load carrying capacity of column (440 kN) was applied on the column and load was gradually increased at the free end of the beam. During pushing first crack was formed in the beam portion approximately at a distance of 65 mm from the face of the column at a load of 24 kN. At a load of 26 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 28 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 30 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 32 kN. During pulling, first crack was formed in the beam portion at a load of 22 kN. At a load of 24 kN, another crack was formed in the beam-column joint of the test specimen. The cracks in the beam started to widen at a load of 26 kN. Spalling of concrete occurred in the tension zone of the beam at a load of 28.5 kN. The application of the load was stopped when the deflection at the free end of the beam reached 50 mm. The load corresponding to this deflection was 30 kN.

Glass fiber reinforced polymer sheets and sisal fiber sheets wrapping almost give the same increase in the load carrying capacity and energy absorption capacity. In the case of hybrid layers consisting of orthogonal mesh of two different types of fiber sheets, the combination of carbon fiber reinforced polymer sheets with any other fiber reinforced polymer sheets gives the maximum increase in the load carrying capacity and energy absorption capacity. It is also found that one layer of carbon reinforced polymer sheet and another layer of any other fiber reinforced polymer sheet wrapping gives almost the same increase in the load carrying capacity and energy absorption capacity.

V. CONCLUSION

- It is found that specimens detailed as per code IS 456:2000 retrofitted with GFRP sheets subjected to reversal load were found to have 19.40 % to 27.20 % more load carrying capacity and 22.20 % to 29.60 % more energy absorption capacity than the specimens detailed as per code IS 456:2000 subjected to reversal load.

- It is found that specimens detailed as per code IS 456:2000 retrofitted with CFRP sheets subjected to reversal load were found to have 30.70 % to 37.30 % to more load carrying capacity and 32.10 % to 42.30 % more energy absorption capacity than the specimens detailed as per code IS 456:2000 subjected to reversal load.

- It is found that retrofitting with carbon fiber reinforced polymer sheets resulted in maximum increase in load carrying capacity and energy absorption capacity. However the cost of carbon fiber reinforced polymer sheets is found to be the highest.

- It is found that retrofitting with glass fiber reinforced polymer sheets resulted in least increase in the load carrying capacity and energy absorption capacity. It is also found that cost of glass fiber reinforced polymer sheets is the least.

- In case of hybrid wrapping, it is found that wrapping with one layer of carbon fiber reinforced polymer sheet along with any other fiber reinforced polymer sheets resulted in maximum increase in load carrying capacity and energy absorption capacity.

- Based on percentage increase in the energy absorption capacity per unit cost, it is found that glass fiber reinforced polymer sheet wrapping is found to be the best in terms of cost effectiveness.

- Based on the workings, it may be concluded that the cost of production of G30, normal strength concrete, is marginally (2.9%) higher than OPC M30 concrete. Therefore, it can be concluded that cost effectiveness can be achieved in the production of high strength concretes.

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