INNOVATIVE METHOD UTILIZING HYBRID FRP SYSTEM FOR SHEAR STRENGTHENING OF CONCRETE STRUCTURES

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ABSTRACT

Fiber reinforced polymer (FRP) materials have widespread use in many different areas of repair and strengthening of RC structures due to their many merits such as low unit weight, excellent corrosion resistance, high strength and ease of handling and application. However, these systems are scarcely applied for enhancing punching shear resistance for RC flat slabs. Moreover, the internationally available codes and guidelines do not recognize punching shear resistance as one of the domains for application of FRP strengthening systems. This research work is an attempt to widen the application of FRP in the field that was regarded as a prohibited area, i.e. enhancing the punching shear resistance of reinforced concrete slab-column connections.

In this work, an innovative system is introduced that utilizes FRP composites for enhancing the ultimate capacity of slabs supported on columns and subject to punching shear. The paper presents a detailed description of the developed solutions; in terms of theoretical design, mode of failure, load transfer mechanism as well as practical implementation of the systems in the construction field. An experimental program was conducted in order to verify the effectiveness of the developed system. The experimental results demonstrate high effectiveness in enhancing punching shear resistance. Additionally, the developed strengthening system has the advantage of speed and ease of application, in addition to being versatile and can be extended for different design problems. By proving the effectiveness of the new system in shear

strengthening; a new area of application has been introduced for FRP systems, that may be applied in a wide range of strengthening and retrofitting applications.

INTRODUCTION

Fiber Reinforced Polymer (FRP) systems have been successfully used for strengthening of reinforced concrete slabs, beams and columns due to their many merits such as low unit weight, excellent corrosion resistance, high strength and ease of handling and application. Sometimes for strengthening or retrofit of existing structures, there is a need for increasing the shear resistance of reinforced concrete sections. This may be due to element damage or deterioration, design or construction deficiencies, design code alterations or new requirements. Need for shear enhancement may occur in the case of strengthening flat slab roof systems, column-footing connections, increasing the punching shear capacity of pile caps, providing enhancing bearing of RC beams on columns or introducing additional beams or floors over existing columns. However, FRP strengthening materials have no existence in the domain of enhancing shear resistance for RC elements such as the previously mentioned cases. Moreover, the internationally available codes and guidelines do not recognize punching shear resistance as one of the domains for application of FRP strengthening systems [1-3]. Published research work related to the usage of FRP systems in the enhancement of punching shear resistance of RC slab-column connections has given unsatisfactory results. The reported results and the lack of positive conclusions in previous research are not due to limitations in FRP systems; but due to the way the FRP was employed. The available research work utilized the FRP as wrapping or sheets spread on the tension surface of the slab; not taking into consideration that the material has no significant out-of-plane resistance; while the maximum strength of the material is achieved in the direction of the fibers [4, 5]. Taking this fact into consideration it is reasonable that the increase in punching shear resistance was not satisfactory. In order to develop an effective system, it would be necessary to utilize the merits of the FRP materials but in a new way different than the existing previous work. It is therefore desirable to explore the possibility of creating a hybrid arrangement where the FRP material plays the role it is most fitted for.

In the present research work, an innovative integrated system is introduced for strengthening reinforced concrete slab-column connections in order to increase the punching shear resistance. The strengthening systems developed represent a non-conventional and innovative approach in all aspects. Enhancement of the punching shear resistance of the system is achieved through blending and integration of both the geometry of the added unit components with the well-known FRP confinement capabilities [6]. The new technique is introduced through theoretical analysis of the basic idea of the system; its geometry, constituents, execution procedure, load transfer mechanism and mode of failure. The technique is characterized by its speed of installation; it is practical for application in the field where there is a need for immediate use of the building or where there is a danger of collapse of the structure. The system can further be extended to a class of strengthening schemes or techniques of the same or similar ideas.

SHEAR STRENGTHENING OF RC SLAB-COLUMN CONNECTIONS

Reinforced concrete slabs supported directly on columns, without beams or column capitals, are subject to shear stress at the connections with the columns can reach values higher than the level provided by concrete thus causing punching failure. This failure is a brittle type of failure that occurs without much warning. Different strengthening methods can be applied in order to increase the punching shear resistance of reinforced concrete slab-column connection. However, some of the traditional methods are time consuming and expensive, while others are destructive.

One of the techniques for shear strengthening of existing slab-column connections is by adding a column head or shear collar. Shear collars are circularly reinforced jackets placed around existing columns for strengthening and repair purposes for reinforced concrete slab-column connections. This is considered a popular retrofit method providing an alternative to other more costly or destructive shear transfer mechanisms, such as anchored dowels, and shear keys. By increasing the perimeter of the load transfer area, the (punching) shear capacity of the slab-column connection can be significantly improved. This also results in increased slab bending capacity because of span reduction [7, 8]. However, proper design of the reinforcement in the column is essential. Shear collars usually use circular reinforcement or lap-spliced reinforcement. Concrete for the shear collar usually is placed by pumping the concrete into the form through vent holes in the form or through a space left between the top of the collar and the slab soffit, later, a stiff mortar is dry-packed into this space. [7]. Another alternative is to pump grout around aggregate pre-placed in the form. For sloping shear collars with a variable collar diameter, a reusable steel form gives desirable aesthetics. For square and rectangular columns, flared capital with plane surfaces may be preferred for aesthetic reasons. Shear collars have been used worldwide successfully for many applications; to strengthen column-footing connections, serving the dual purpose of repairing the deteriorated column bases and transferring the loads from the columns to the footings, thereby bypassing the deteriorated column areas and increasing the punching shear capacity of pile caps. Additionally, shear collars were placed around existing columns near mid-height in order to support supplemental floor framing. Concrete shear collars have also been used to increase the capacity and ductility of slab-column connections in existing structures located in seismic zones. They may also be used to provide supplemental confinement to column reinforcement at column-slab or at column-footing connections, thus providing seismic retrofit [9]. Another application of shear collars is using them as jacking surface for the replacement of bridge-girder bearings. Installing a permanent shear collar at top of the column may provide additional area to facilitate jacking [8].

In the shear collars placed around existing columns, because no reinforcement crosses the potential slip-plane, the usual shear friction mechanism does not occur. Instead the radial compression resulting from tension of the circular confining reinforcement develops the normal force. The reinforcement is tensioned when the collar expands and begins to slip on a roughened surface. Shear friction load transfer between collar and column necessitates that the circular confinement around a square column ensures that the usual shear friction failure mechanism is prevented. Instead, the radial compression resulting from tension of the circular confining reinforcement develops a normal force. The expansion of the collar due to the normal force is prevented by the FRP wrapping which is particularly efficient in the case of circular confinement. FRP gives higher confinement than circular steel stirrups, as carbon fibers have higher stiffness than steel. When the column tends to expand transversely under the effect of excessive axial loading, thus tensile force developed in the fibers will be higher than in case of steel, thus providing more confinement to the concrete axially loaded element. This means that the confinement limit of the jacket will be stiffness-controlled and not strength controlled; where the FRP surpasses the steel jacket. This was confirmed by the observations and results obtained from the experiments, as will follow.

INNOVATIVE FRP HYBRID SYSTEM

The proposed system has an advantage over the traditional methods in making use of FRP confinement capabilities to reach results unachieved before using other implementation techniques. To construct the hybrid FRP collar system the following steps are executed [6]:

Step 1: Adding reinforcement for the collar

The column surface at the slab column connection is roughened. Steel bar dowels, acting as shear connectors are anchored to the column face by extending the two ends of each dowel into holes drilled through the column; with addition of side reinforcement in the form of cantilever to the four sides of the column. Closed horizontal stirrups each consisting of two U- shaped parts linked together are added as required. Anchorage is achieved through injecting epoxy into the holes. Figs. 2 and 3 illustrate the arrangement for shear reinforcement of column collar and for slab.

Step 2: Casting the collar

A reusable cylindrical steel form is added around the column, casting can be done through injecting grout material through a nozzle included at the bottom of the form, until the grout is emitted through a nozzle at the top of the form. Another alternative would be to inject the grout from the upper side of the slab through a hole drilled in the slab; both techniques are explained in Fig.4.

Step 3: Wrapping CFRP sheets

After removing the form by suitable time; CFRP sheets are wrapped around the external perimeter of column head by means of epoxy resin that will ensure confinement for the newly created collar. The final schematic of this solution is shown in Fig. 5.

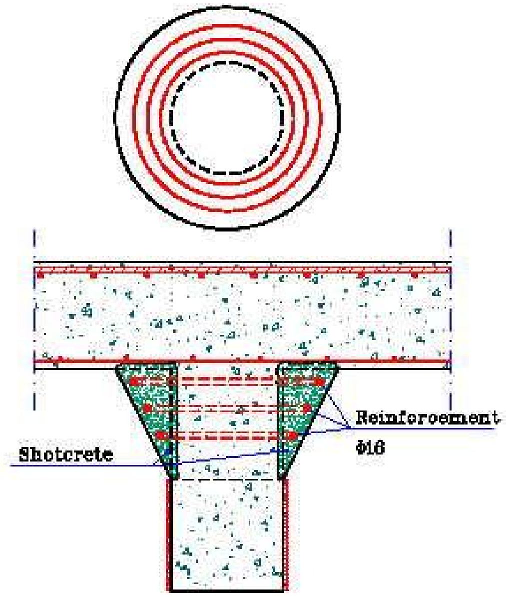


Fig. 1 Installation of column head / shear collar

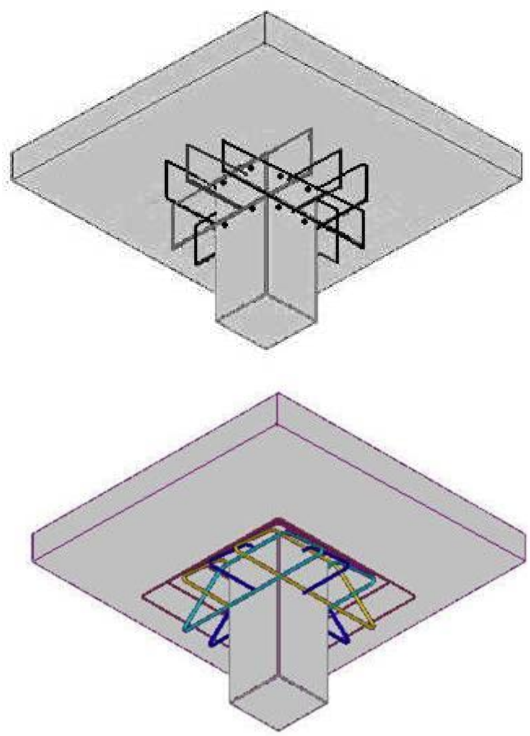


Fig. 2 System for reinforcement of the column head

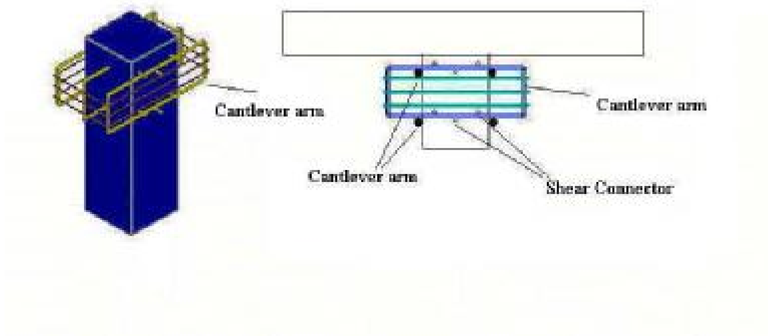


Fig. 3: Shear reinforcement for collar system

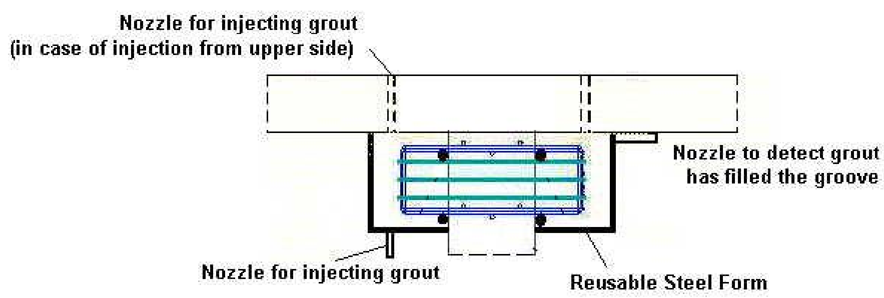


Fig. 4: Casting the collar

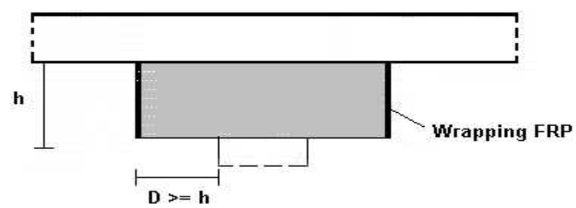


Fig. 5: Column head wrapped with FRP

EXPERIMENTAL PROGRAM

An experimental investigation has been conducted in order to validate the developed innovative technique for strengthening RC flat slab-column connections and to determine its efficiency in enhancing punching shear resistance of such slabs. The following sections give detailed description of the test program, test specimens, material properties, test setup and test procedure of tested specimens. The experimental study investigates the developed method in addition to methods available in the published research employed to create a pyramidal head for the column. A total number of 30 concrete column head connections were subjected to vertical shear load and flexural load using hydraulic compression jack machine of 300-ton capacity. The experimental program was executed at the Arab Contractors Central Laboratory of Strength of Materials.

Test Specimens:

Concrete The mixes used to cast the specimens were designed to get target cubic compressive strength of 250 kg/cm^2 after 28 days, through trial mixing using locally available materials. The materials used for concrete mix are fine aggregate, coarse aggregate, cement, water and super plasticizer. The coarse aggregate was crushed dolomite size no.1 and 2 from the Suez Mountain. The fine aggregate was clean sand almost free of impurities from El-Khatatba quarries. Ordinary Portland cement from Tora Cement Company complying with Egyptian Standard Specifications 373-1991 was used. The super-plasticizer used was Cockrete G_n, a powerful water reducing agent in concrete mixture (type G), which is a product of El Nasr for Cock manufacturing Company.

Mix proportions The mix proportions shown in Table 1 lists the quantities for one cubic meter of concrete to achieve target strength of 250 kg/cm^2 after 28 days. Three cubes were tested under compression at the same day of testing each slab-column connection test to determine the compressive strength of concrete f_{cu}.

Table1. Mix proportions by weight for 1m^3 concrete

Compressive target strength kg/cm2	Cement (Kg)	Crushed dolomite (Kg)	Sand (Kg)	Water (Liter)	Super-plasticizer (lt)
250	350	1110	670	170	3

Steel Reinforcement Different reinforcement diameters and types were used in this study. High tensile steel bars 10, 16 and 19 mm diameter and mild steel of 8 mm diameter were used. Reinforcement arrangement of the column head is shown in Fig.2.

Strengthening Materials

The materials used as part of the external strengthening system of the test specimen against punching shear, are listed in Table 2. Detailed description of those materials and their properties are given in the references [11-13] and in the following sections and tables.

Table 2. Materials used for strengthening

Material	Usage	Material Name (commercial brand)
High strength polyester resin bonding and repair compound	Fixing steel bar dowels to column head	CONCRESIVE ® 1418 [11]
High strength, shrinkage compensated cementitious micro concrete	Grout material for filling pyramid groove in drop panel	MASTERFLOW ® 98CM [12]
CFRP Composite Strengthening System	To provide complete confinement of the strengthening system	MBT- MBrace™ FRP Strengthening System consisting of: MBT-MBrace™ Primer MBT-MBrace™ Saturant MBT- MBrace™ CF 130 Fiber Sheets [13]

a) High strength polyester resin bonding and repair compound

A product of Degussa Construction Chemicals, CONCRESIVE® 1418, [11], a two-component polyester resin compound consisting of a liquid resin and a powdered hardener filler system. Mixing the powder and liquid components of starts a chemical reaction; producing a material of exceptional strength and chemical resistance. It is considered a repair, bonding and grouting material with physical properties given in Table 3.

Table 3: Typical properties of CONCRESIVE® 1418 [11]

Density	1920 kg/m^3	
Setting times	15ºC	2 hours
	20ºC	1 hour
	25ºC	30 minutes
	35ºC	17 minutes

b) High strength, shrinkage compensated cementitious micro concrete

MASTERFLOW® 98CM, a product of Degussa Construction Chemicals [12], a ready to use product in powder form, which requires only the on-site addition of water to produce a shrinkage compensated micro concrete of predictable performance.

Table 4 Typical water requirements [12]

Application	Consistency	CRD-C-588-79	FLOW-CONE CRD-79	Mix water liters / 25 kg	
				min	max
Grouting machinery	Fluid	-	25-35	3.25	3.5
Grouting machinery	Flowable	130	-	2.8	3.25
Bedding pre-cast	Plastic	60	-	2.0	2.5
Filling tie-bar voids	Dry-pack	-	-	1.5	1.75

The strength development of grout is dependent on many factors such as mixing, water addition, curing, temperature and humidity. Table 5 gives typical average strengths of MASTERFLOW 98® CM at 25”C, when mixed with 2.8 liters (flowable) and 3.5 liters (fluid) per 25kg bag.

Table 5 Compressive Strength of Grout [12]

Time	Compressive strength	
	Flowable N/mm^2	Fluid N/mm^2
1 DAY	35	28
3 DAYS	50	35
7 DAYS	60	45
28 DAYS	65	58

c) Carbon Fiber Reinforced Polymer CFRP composite strengthening system

The composite strengthening System used in the experimental work is MBT-MBrace™ FRP, product of Degussa Construction Chemicals [13] and consists of:

- ***Primer*** - improves the bonding of the composite to the substrate, it is the concrete bonding adhesive for use with the CFRP sheets.
- ***Saturant*** - adhesive for fiber sheets, it is the epoxy resin for bonding carbon fiber sheets. It is a 100% solid, non-sag paste epoxy resin material.
- ***Carbon Fiber Sheets*** - fiber reinforcement. Composite Materials included are the **MBT MBrace™ CF 130**. [13].

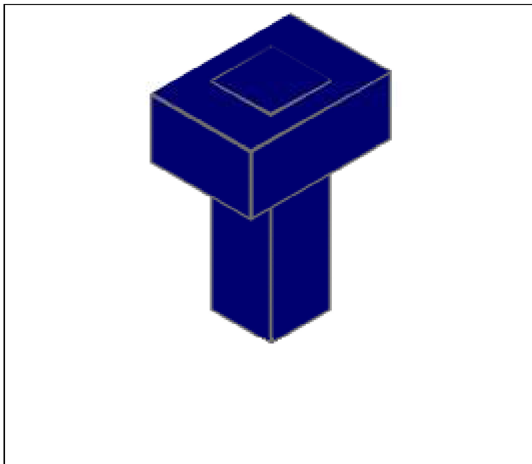
Table 6: Typical Physical properties of CF 130 [13]

MBT-MBrace™ CF 130: Carbon Fiber Reinforcement System-High tensile CF	
Modulus of elasticity	240 GPa
Tensile Strength	3,800 MPa
Weight of C fiber (main direction)	300 g/m^2
Density	1.7 g/cm^3
Є Ultimate %	1.55%
Thickness	0.176 mm
Design Tensile force at 0.6% strain/m width	211 kN

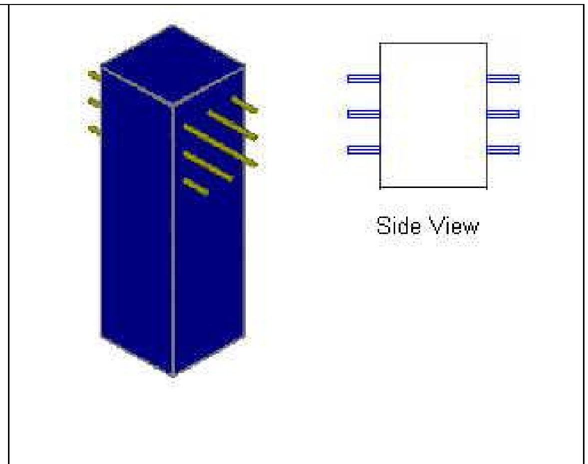
Preparation of Test Specimens:

In this phase the test specimens used were thirty (30) short columns 15 x 15 x 30 cm. The moulds used were metallic prisms with faces at right angles to each other and to the axis of the prism. The internal surfaces of the moulds were oiled before use, and a suitable sealant was used to prevent leakage through the joints. The test specimens were prepared from fresh concrete according to standard specifications. Concrete ingredients previously mentioned were mixed mechanically for four minutes, then placed inside the moulds and vibrated with an electrical rod type vibrator, and then the specimen surface was leveled by screed. Different arrangements of steel dowels and stirrups were used to resist shear and also FRP was used to increase confinement of the column head.

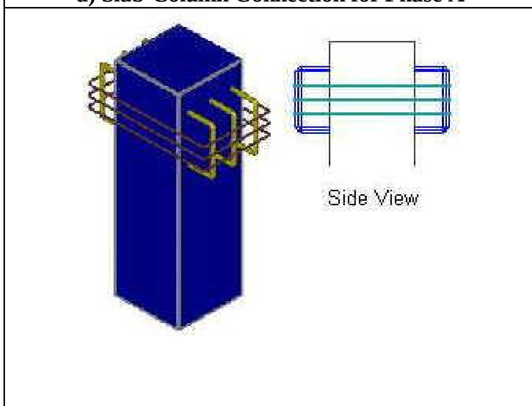
Different systems were used to add 15 x 15 x 10 cm column head to the short column specimens used. Figure 8 shows diagrammatic schemes illustrating the details of the different systems used in the tested column connections. According to the systems of head fixation the specimens were divided into 5 groups, named cc1 to cc5, each group consisted of 6 specimens.



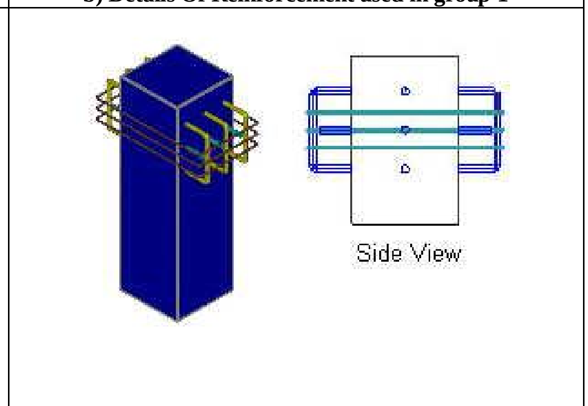
a) Slab-Column Connection for Phase A



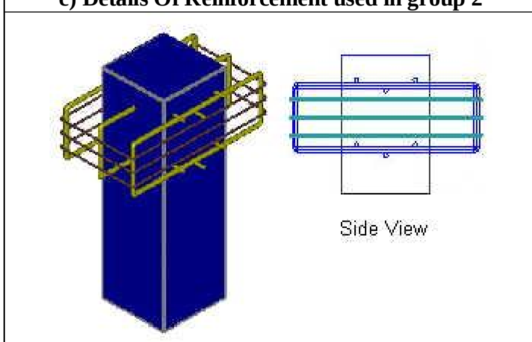
b) Details Of Reinforcement used in group 1



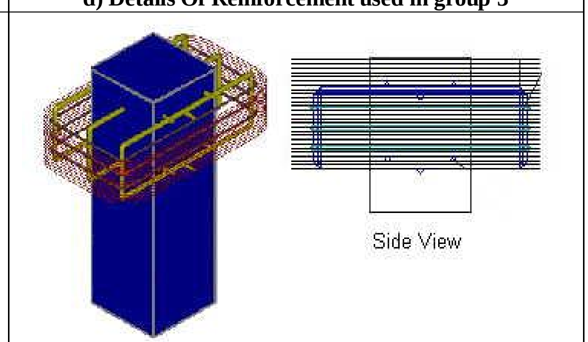
c) Details Of Reinforcement used in group 2



d) Details Of Reinforcement used in group 3



e) Details Of Reinforcement used in group 4



f) Details Of Reinforcement used in group 5

Fig.6 Details of short column specimen used

Experimental Set-Up And Test Procedure

The 5 groups of column head connections named cc1 to cc5 were tested under the effect of shear and flexural load. Three specimens were tested for each group of column head and their average value for shear loads and moment loads were taken to represent the load capacity for each system of strengthening.

a) Tests of column head connections subject to shear loads

The maximum shear load for column head specimens is determined by testing all specimens for each group of column heads, using a 1200 kN Universal Testing Machine (Toni-MFL) at Arab Contractors Central Laboratory. The test consists of applying axial compressive load to the column head. The test setup as well as the supports location is shown in Fig. 7 and Fig. 8 a).

b) Tests of column head connections subject to moment load

The test consists of applying axial compressive load to the column head supported by symmetrical two-point at a distance of 7 cm from the face of columns as shown in Fig. 8 b).

Fig. 7 Test of column head connection subject to shear loads

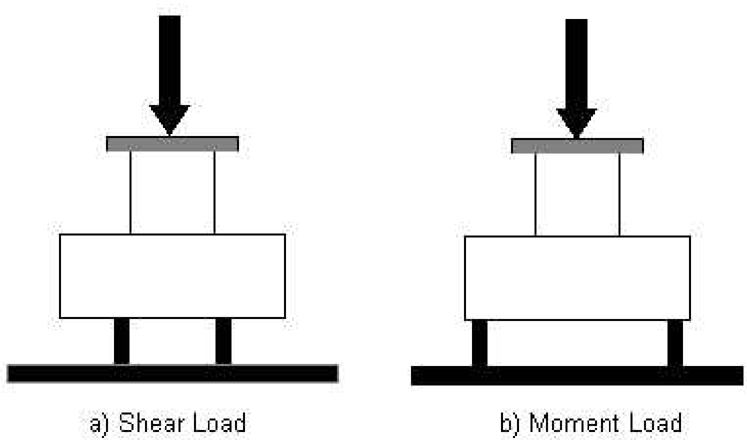


Fig. 8 Test of column head connection

INTERPRETATION AND DISCUSSION OF EXPERIMENTAL RESULTS

The experimental results given in Table 8 show the ultimate shear and moment load recorded for the tested reinforced concrete column-head specimen.

Table 8 Results for tested column head test specimens

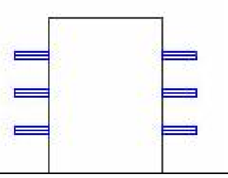
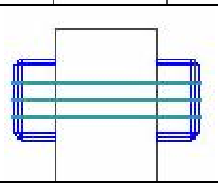
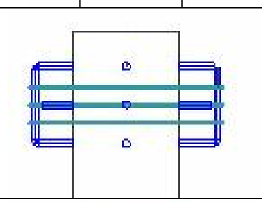
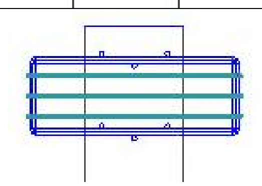
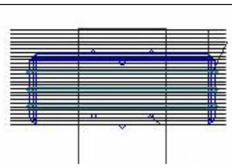
Group	Reinforcement scheme for Column head	Details of Shear Reinforcement	Max. Loadfor shear (ton)	Max. Load for moment (ton)
1		Straight Bar 9Φ10 in each face, spacing 4 cm	65	4
2		U-shaped Bar 3Φ10 in each face, spacing 4 cm with closed stirrups 3Φ10 spacing 4 cm	67	17
3		U-shaped Bar 3Φ10 in each face, spacing 4 cm + 3Φ10 straight bar in the middle, with closed stirrups 3Φ10 spacing 4 cm	71	22
4		2-side cant lever U-shaped Φ10mm + U-shaped Bar 1Φ10 in each face + 1Φ10 straight bar in the middle, with closed stirrups 3Φ10 spacing 4 cm	79	37
5		Same reinforcement used in group 4 in addition to FRP wrapping of the outer perimeter of the column head	82	59

Table 9 Comparison between test results and maximum load achieved

Group	% Shear Load increase*	% Moment load increase*
1	97%	23%
2	100%	100%
3	106%	130%
4	118%	218%
5	122%	350%

** Relative to group 2*

The obtained results show the following:

- Group 5 achieved the maximum shear load and maximum moment resistance, 82 ton and 59 ton, respectively.
- For group 1, the straight bar, though requiring minimum penetration depth, achieved high shear resistance; but the moment resistance was negligible.
- For group 2 and 3, the addition of stirrups improved the moment resistance.
- For group 4, the addition of side cant lever bars improved moment resistance significantly (218%) and shear load was increased by 118% relative to group 2.
- For group 4 and 5, the addition of the CFRP in group 5 raised shear resistance by 4% and increased moment resistance by 132% over group 4.

A comparison between load for shear and moment for the different groups are given in Table 9. The comparison figures are relative to Group 2 as Group 1 achieved no significant results for moment as expected. From the above analysis, it can be seen that group 5 achieved the highest results in both shear and moment and showed the effect of FRP wrapping. Also, it is important for this system to have the maximum moment resistance possible. Therefore group 5 is considered as an effective strengthening technique and constitutes an innovative hybrid FRP collar system for upgrading of slab-column connections.

CONCLUSIONS

This research work presents an innovative hybrid strengthening system that incorporates the superior tensile capabilities of FRP materials and integrates it into a carefully designed geometric formulation in order to achieve maximum possible overall behavior. A methodology for the practical construction procedure is described for strengthening measures of existing RC structures utilizing the developed innovative strengthening system. Moreover, the experimental program conducted through this work demonstrated the applicability and efficiency of the developed system.

The developed technique thus represents an innovative hybrid FRP system suitable for a vast range of retrofit and strengthening applications that necessitates upgrading of the shear resistance of reinforced concrete structural assemblages. The developed hybrid FRP shear collar system showed effectiveness in enhancing punching shear resistance for external strengthening of slab-column connections against punching shear. The ease and speed of application renders it suitable for application in the fields where there is a need for immediate use of the building or where there is a danger of collapse of the structure. The developed strengthening system is a versatile hybrid system which efficiently utilizes the well-pronounced confinement capabilities of FRP and may be adapted for different applications. The system can also be used to strengthen column-footing junctions when there is an increase in column loads or a deficiency in concrete footings. Additionally, it can provide possibility of addition of a new concrete floor between existing floors or between the basement and the existing first floor or similar applications involving providing or enhancing bearing.

The present study is believed to provide a practical system in terms of ease of application, time to setup and operate as well as cost-effectiveness, suitable for any upgrading or rehabilitation project. The system presented is also highly versatile, economically competitive and effective technique for enhancing punching shear resistance of RC slabs to any load value according to the strengthening requirements. By proving the effectiveness of the new system in strengthening against punching shear; a new area of application is discovered for FRP systems, which are considered one of the most promising technological advances in materials and structural engineering but have yet been scarcely utilized in the area of punching shear resistance.

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