Optimization of GFRP Confinement in RC Columns using Shape Modification Technology

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***Abstract* - It is a known fact that the performance of conventional concrete is enhanced by external fibre reinforced polymer confinement (FRP). This technique is considered superior to steel jacketing methods in terms of confinement strength, ductility, sectional areas, weight, corrosion resistance, ease of installation and overall cost. This paper presents an experimental study focuses to find the effect of corner shape modification in square column on FRP properties and to achieve whether the former is suitable for high strength concrete or low strength concrete. Here a study on the behaviour of axially loaded short reinforced concrete columns that have been strengthened with glass fibre-reinforced polymer sheets (GFRP). Both circular and square reinforced concrete columns, forming a total of 42 specimens were loaded to axial compression and investigated in both axial and transverse directions. The parameters considered are strength of concrete, cross sectional shape and GFRP type. The experimental results clearly shows that GFRP confinement enhances the compressive strength and ductility of circular columns more effectively than square columns which is a known fact, but this increase in strength and ductility is more significant for low strength concrete. In addition, bi-directional yields better result comparing with chopped strand.**

Keywords: Strength of RC column, GFRP, confinement, section shape

1.0 INTRODUCTION

Strengthening and upgrading of newly built and existing structures are standing in the first among the major challenges that civil engineers is currently facing. The best answers to these needs is the use of external confinement of RC members using fibre reinforced polymer sheets. Such strengthening technique has proved to be very effective in enhancing their ductility and axial load capacity. Several studies on the performance of FRP wrapped columns have been conducted, using both experimental and analytical approaches. However, the majority of such studies have focused and discussed below.

Study concentrated on composites layers and Fibre direction indicates that the strength of concrete cylinder increases in direct proportion to the number of composite layers[1]. The main purpose was to investigate the effect of corner radius on the effective confinement that is provided by CFRP jackets. The test variables included the corner radius ratio and thickness. Test results indicate that corner radius is of great importance in relation to the level of confinement[2]. This study presents an experimental investigation on the behaviour of axially loaded short rectangular columns strengthened with CFRP wrap and this confinement enhances the performances of the rectangular columns but is more effective in case of square column.[3]. A series of tests on CFRP confined concrete with varying corner radius were done in which the results clearly shows that the corner radius ratio is in direct proportion to the confined concrete strength whereas the sharp corners is insignificant in increasing the strength of columns[4]. Tests on square prismatic concrete columns, strengthened with external GFRP clearly demonstrates that composite wrapping enhances the structural performance of concrete columns under axial loading[5]. Based on the analysis of experimental results and the performed analytical verification, the efficiency of the confinement was very sensitive to the specimen cross-section geometry and the confining stress expressed in the number of the GFRP sheet layers applied and in addition it enhances the structural performance of concrete columns[6]. Uniaxial compression tests on CFRP jacket confined columns have shown that the increase of ultimate strength is highly influenced and increases with the radius of the corners of square sections. On the other hand, the increase of axial deformation capacity is up to 8 times that of unconfined concrete, even for the sharp edged sections[7].) Here the confinement models show little improvement in high strength concrete due to confinement, but no significant improvement in ductility is expected[8]. Experimental work on mechanical properties of GFRP plates with different fibre volume fraction(v_f) shows that the former was improved when v_f is increased[9]. Studies on concrete cylinders confined with CFRP with varying fibre thickness and orientation clearly explains a significant enhancement in the compressive strength and ductility compared to unconfined concrete cylinders[10]. Shape modification using expansive cement concrete and prefabricated FRP shells changes confinement from passive to active and achieves a higher axial compressive strength and strain for modified square and rectangular columns compared to the original columns[11]. A performance based approach is presented for the design of confining FRP reinforcement externally applied to square concrete columns show that the confinement design parameters such as the amount of FRP reinforcement and FRP strength to the column's ductile performance and the required amount of confining FRP increases with an increase in ductility demand[13] . Focusing on the effects of corner radius on FRP mechanical properties shows that corner radius plays a vital role on mechanical properties and in addition increasing the FRP plies from one to two significantly improved the efficiency[14]. From the above studies, it is crystal clear that FRP wrapping increases the structural performance circular column than square column. The data available for, what should be done to increase the performance of square column in order to match with the circular column are still limited and remains in its developmental stages. For that the square columns are cornered, in which the increase in performance of square column seems to be approximately equal to circular FRP wrapped column. This paper specially deals with the optimization of GFRP wrapping for different concrete mixes ie) whether it is suitable for normal strength concrete mix or high strength concrete mix.

An experimental investigation has been conducted with a series of tests on circular and square reinforced concrete columns (RC) strengthened with glass fibre reinforced polymer sheets. A total of 42 reinforced concrete specimens were tested under axial compression. The parameters considered are cross section shape (circular and square), the compressive strength of concrete (normal strength 25 MPa and high strength 50 MPa)

All specimens were loaded to failure in axial compression and investigated mostly in both axial and transverse directions.

2.0 EXPERIMENTAL PROGRAM

2.1 Material properties

2.1.1 Concrete

In order to investigate the influence of FRP confinement on concrete mix, two different kind of concrete mix have been taken to represent normal strength (I) and high strength concrete (II) respectively. The strength and the quantities of ingredients, used in the concrete mix are shown in table 1.

Table 1. Concrete mixture proportions

Concrete mixture No.	I	II
Concrete strength, MPa	25.93	50.35
Cement, Kg/m^3	383.2	450.95
Water, Kg/m^3	191.6	139.98
Coarse Aggregate, Kg/m^3	1148.5	1247.58
Sand, Kg/m^3	608.63	611.54
Chemical admixture, ml	-	8.8
Water/Cement ratio	0.5	0.318

2.1.2 Reinforcement steel

For all the RC specimens the diameter of the longitudinal and transverse reinforcing bars were 12mm and 6mm respectively. The longitudinal steel ratio was constant for all square column. The yield strength of longitudinal and transverse reinforcement bars are 415 MPa and 415 MPa respectively. Forms of square specimen and the corresponding tied reinforcement cage are shown in fig.1

Fig .1

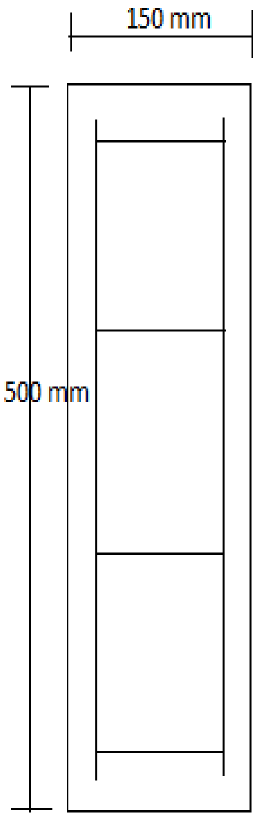
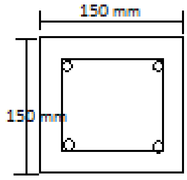
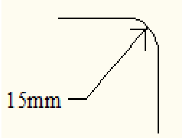
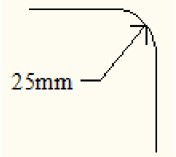
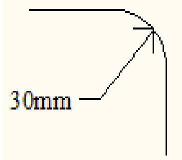
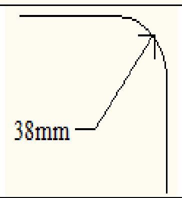
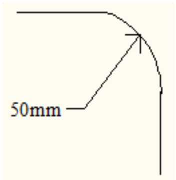
2.1.2 GFRP laminate

The glass fibre reinforced polymer sheet used here are chopped strand and bidirectional (woven). Vinyl ester resin was used to bond the glass fabrics over the concrete columns.

2.1.3 Specimen details

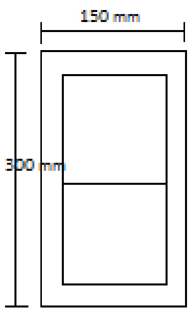
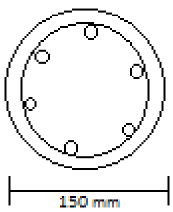
The experimental program in terms of specimen's details, test setup, instrumentation and test procedure was conducted. This includes concrete cylinders and reinforced square columns. *Table 2* shows the properties and dimensions of the specimens. The specimen notations are as follows. The first letter denotes cross section shape: S for square column and C for cylindrical column. The next two refers to the concrete mixture: I for normal strength concrete and II for High strength concrete followed by corner radius. The last number specifies the number of layers.

Table 2. Square Specimen Design

Elevation	Cross Section	Corner Radius (r) mm	r / b	Aspect Ratio	Designation
 Long.rft : 10ϕ 4 Stirrups : 6ϕ at 150 mm		5 mm	1/30	3.33	SN05 SH05 SNC05 SNW05 SHC05 SHW05
		15 mm	1/10		SNC15 SNW15 SHC15 SHW15
		25 mm	1/6		SNC25 SNW25 SHC25 SHW25
		30 mm	1/5		SNC30 SNW30 SHC30 SHW30
		38 mm	1/4		SNC38 SNW38 SHC38 SHW38
		50 mm	1/3		SNC50 SNW50 SHC50 SHW50

r - the radius of the corner of the square specimen ; *b* - breadth of the square specimen ;

Table. 3 Cylindrical Specimen design

Elevation	Cross Section	Corner Radius (r) mm	r / b	Aspect Ratio	Designation
	 Long.rft : 8ϕ6 Stirrups:6ϕ150	75 mm	1/2	2	CN75 CH75 CNC75 CNW75 CHC75 CHW75

2.2 Specimen preparation

2.2.1 Concrete specimen

Specimens of reinforced square columns with a dimension of 150mm by 150mm cross section and 500 mm height with corner radii of 5mm, 15mm, 25mm, 30mm, 38mm, 50mm, 75mm were prepared. One of each group were used as control specimen and the remaining were wrapped with one layer of GFRP. Cylindrical specimens were made, out of which each one from high strength and low strength were used as control specimen. The remaining were wrapped with one layer of GFRP sheet.

Forms for the square column specimens were prepared using plywood sheets cut and assembled to provide 90º corners. In order to round off the corners of the square specimen, PVC pipes with the desired radius were cut and glued to the corners of the boxes whereas steel cylindrical moulds were used. Casting of the test specimens were made. Although the bottom of the specimens was formed, the top surface was finished very carefully using steel trowel to ensure a level surface. The concrete mix was slowly poured into the forms to prevent segregation and vibrator was used to vibrate the concrete carefully, to prevent voids from forming.

2.2.1 GFRP Jacketing

After 28 days of curing, the GFRP sheets were applied to the specimens by manual wet lay-up process. The concrete specimens were cleaned and completely dried before the resin was applied. The mixed vinyl ester resin was applied directly on to the substrate. The fabric was placed carefully into the resin with gloved hands and smooth out any irregularities or air pockets. Finally a layer of resin was applied to complete the operation. The wrapped specimens were left at room temperature for one week for the vinyl ester resin to harden adequately before testing. A total of 78 specimens were wrapped with GFRP sheets, among which 39 numbers of normal strength specimens and 39 numbers of high strength specimens were wrapped with chopped strand whereas the remaining were wrapped with bidirectional woven roving type GFRP. Prior to loading the specimens onto the test machine, the ends of the sheets were ground smooth to remove any uneven edges.

Fig.2 Concrete specimens

2.3 Instrumentation and Testing

The load was applied using universal testing machine which has a vertical load capacity of 100 tonne. Specimens were loaded under a monotonic uni-axial compression load up to failure. Load cell under the specimen was used to capture the axial load readings. The load cell and the LVDTs (linear variable differential transducers) were attached to data acquisition system and checked for readings.

EXPERIENTAL RESULTS AND DISCUSSION

Test Results

All the confined and unconfined Specimens are loaded under monotonic uni-axial compression load up to failure. The obtained values and their corresponding graphs are shown in table 4 and figures below

Table. 4 Experimental Results

Designation	Max. Load (KN)	Max. Defln (mm)	Max. Stress (MPa)	f_{co}	f_{cc}	f_{cc}/f_{co}	% Gain
SN	666.67	1.64	29.63	28.63		1.00	-
SNC05	750.00	1.77	33.33	-	33.33	1.12	12.50
SNC15	941.33	2.01	41.84	-	41.84	1.41	41.20
SNC25	1050.00	2.13	46.67	-	46.67	1.57	57.50
SNC30	1141.33	2.20	50.73	-	50.73	1.71	71.20
SNC38	1233.67	2.39	54.83	-	54.83	1.85	85.05
SNC50	1475.33	2.73	65.57	-	65.57	2.21	121.30
CN	625.00	1.50	27.78	27.78	-	1.00	-
CNC75	1429.67	2.54	63.54	-	63.54	2.29	122.08
SH	1291.33	2.92	57.39	57.39		1.00	-
SHC05	1309.00	3.02	58.18	-	58.18	1.01	1.37
SHC15	1391.00	3.11	61.82	-	61.82	1.08	7.72
SHC25	1450.00	3.20	64.44	-	64.44	1.12	12.29
SHC30	1491.67	3.27	66.30	-	66.30	1.16	15.51
SHC38	1534.33	3.32	68.19	-	68.19	1.19	18.82
SHC50	1633.67	4.01	72.61	-	72.61	1.27	26.51
CH	1240.00	2.75	55.11	55.11		1.00	-
CHC75	1583.67	3.93	70.39	-	70.39	1.28	27.72
SNW05	775.33	1.90	34.46	-	34.46	1.16	16.30
SNW15	957.33	2.06	42.55	-	42.55	1.44	43.60
SNW25	1066.00	2.11	47.38	-	47.38	1.60	59.90
SNW30	1159.33	2.27	51.53	-	51.53	1.74	73.90
SNW38	1258.33	2.36	55.93	-	55.93	1.89	88.75
SNW50	1500.00	2.78	66.67		66.67	2.25	125.00
CNW75	1433.00	2.62	63.69	-	63.69	2.29	129.28
SHW05	1333.33	3.36	59.26	-	59.26	1.03	3.25
SHW15	1416.00	3.42	62.93	-	62.93	1.10	9.65
SHW25	1466.00	3.89	65.16	-	65.16	1.14	13.53
SHW30	1525.00	4.03	67.78	-	67.78	1.18	18.09
SHW38	1558.33	4.38	69.26	-	69.26	1.21	20.68
SHW50	1658.67	4.68	73.72	-	73.72	1.28	28.45
CHW75	1637.67	4.33	72.79	-	72.79	1.32	32.07

Maximum Load Vs Deflection.

The maximum loads of wrapped and unwrapped specimens and their corresponding deflection which is said to be maximum are obtained from load-deflection curve.

Fig.3 Corner radius (r) = 5mm

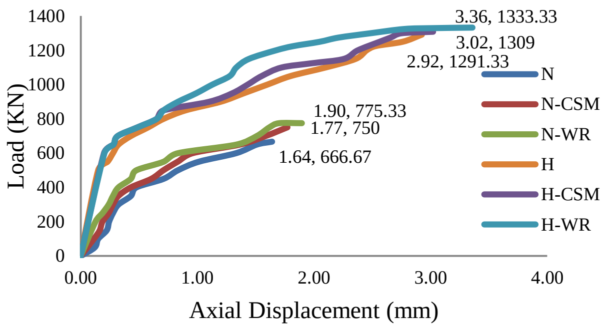


Fig.4 Corner Radius (r) = 15mm

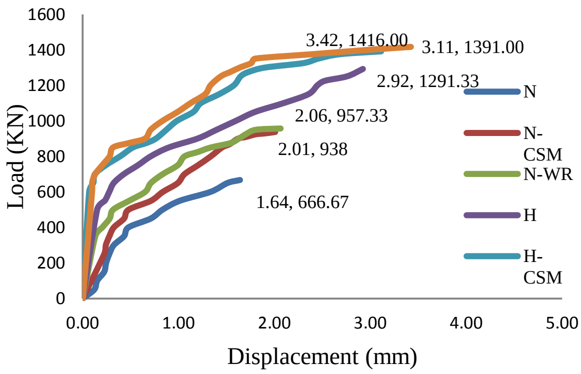


Fig.5 Corner Radius (r) = 25mm

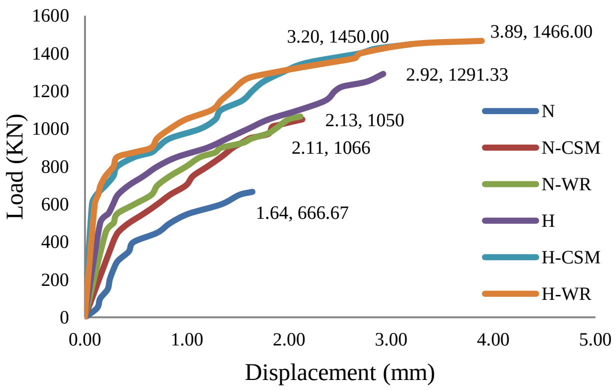


Fig.6 Corner Radius (r) = 30mm

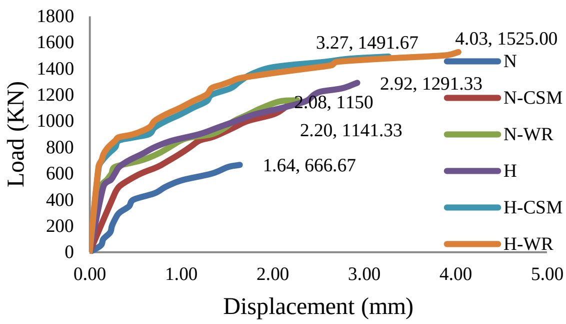


Fig.7 Corner Radius (r) = 38mm

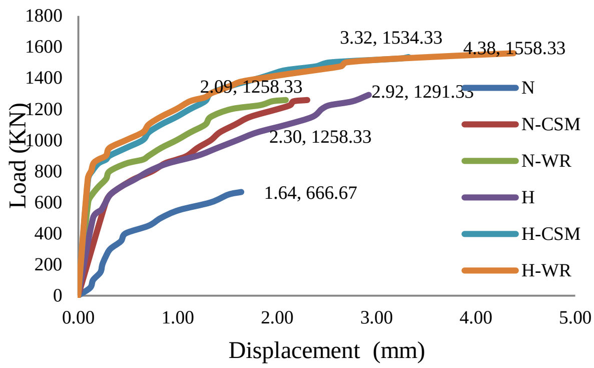


Fig.8 Corner Radius (r) = 50mm

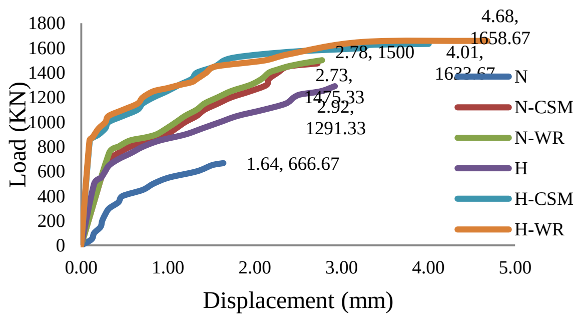
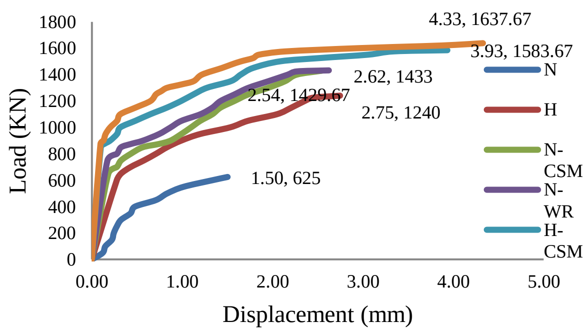


Fig.9 Corner Radius (r) = 75mm

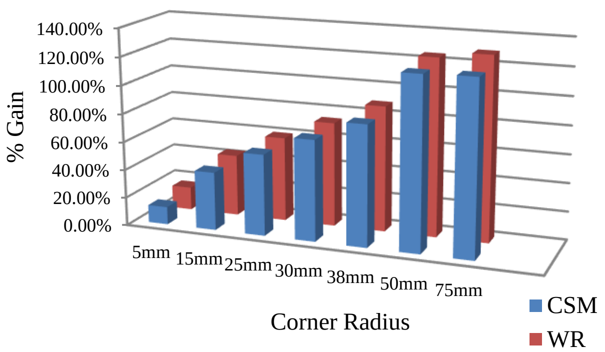


Representative load-displacement curves for each series of tested GFRP wrapped specimens are reported in above fig. for various corner radius. It can be seen that similar to solid concrete reinforced concrete column, FRP external confinement can increase the strength and ductility of the RC columns. The gain in strength is significant for normal mix concrete columns. However, the gain in strength is more considerable when the corner radius is large (50mm). Meanwhile the gain in strength in high strength concrete columns is not much efficient as in normal concrete columns. Also wrapping columns with FRP allows columns to undergo a much larger deflection than unwrapped columns

Effect of Corner Radius

Shape modification of concrete specimen upgrades the load carrying capacity of square concrete columns. The effect of corner radius on normal strength confined concrete (*fig*) and high strength confined concrete, whereas the confinement is made using Chopped Strand Mat (CSM) and Woven roving (WR) are shown below as a bar chart. The chart is drawn between percentage of stress gain along Y-axis and confined specimen corner radius along X-axis

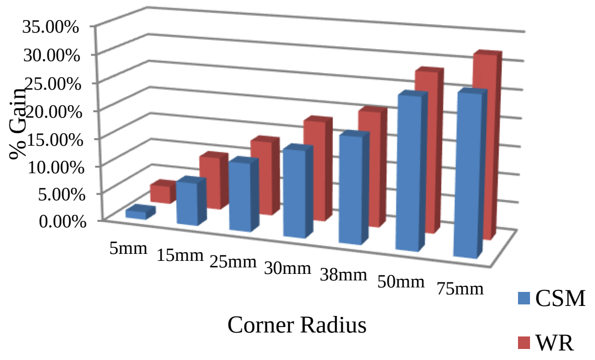
Fig.10 Effect of Corner Radius on Normal strength confined specimen



The maximum stress gain of 121% and 125% is obtained for CSM and WR wrapped normal strength square specimens with 50mm corner radius. Stress gain of 122% and 129% for cylindrical CSM and WR wrapped specimens. This percentage gain increases gradually from 5mm to 50mm. External confinement using shape modification enhances the load bearing capacity of square column in which such increase in capacity approximately equals to the cylindrical confined column. the greater the corner radius the more the stress gain.

In case of high strength confined specimens, the maximum percentage gain is 26.5% and 28.4% for CSM and WR wrapped square specimens. Specimens with 50mm corner radius yields this higher value. For CSM and WR wrapped cylindrical specimen the stress gain are 27.72% and 29.68%.

Fig.11 Effect of Corner Radius on High strength confined specimen



By comparing the above specimens with corner radius 5mm, 25mm, 30mm, 38mm, 50mm and cylindrical specimens, it is easily concluded that (1)confinement increases the performance of cylindrical specimens than square column concrete. (2)If the same confinement accompanied with cornering of square column, the stress enhancement nearly matches with the cylindrical enhancement values. (3)Among Chopped Strand Mat (CSM) and Woven roving (WR), the later shows better result. (4)From the above drawn bar charts, Normal strength concrete specimen shows a better response to external confinement than High strength concrete specimens

3.0 FAILURE MODES AND DISCUSSION

Compression behaviour of GFRP wrapped specimens was mostly similar in each series in terms of failure modes of the specimens. The mode of failure can be characterized by shearing and splitting of the concrete in the control specimens. In these specimens, as the corner radius increases the splitting of concrete becomes uniform along the height, and it becomes almost vertical for the cylinder . For the jacketed specimen, as the corner radius increases, the mode of failure becomes sudden and more explosive. Especially for all cylindrical GFRP confined specimens, collapse was due to fibres rupture and occured in a sudden and explosive way and was only preceded by the discoloration of the resin and some creeping sounds. The location of failure was observed mainly in their central zone, sometimes at more than one location, then delamination spreads towards other sections. regarding confined concrete columns, failure initiated at or near a corner, because of the high stress concentration at these locations. Collapse occured almost without advance warning by sudden rupture of the composite wrap. However, popping noises were heard during various stages of loading and were attributed to micro cracking of the concrete.

Glass fibre wrapped specimens typically failed by a fracture of GFRP composite at or near the corner of the specimens due to the stress concentration in those regions. In all cases, the columns failure was the result of the rupture of the FRP jacket. For most wrapped columns, it was associated with concrete crushing at or near the column ends and marked by wraps rupturing in the circumferential direction. Approaching failure load, the appearance of white patches was found, which indicated the yielding of E-glass and resin. After failure, disintegrated concrete was found. Failure of GFRP wraps was observed at or near a corner in all the specimens mainly due to stress concentrations. This may be expected since the column's sharp edges were not rounded off. In order to avoid stress concentration, an attempt should be made to round off sharp corners. Failure modes of confined and unconfined specimens are shown in fig.12 & fig.13

Fig.12 Failure modes of columns and GFRP torn at the level of corners

Fig.13 Failure modes of Unconfined specimens

5.0 CONCLUSION

Based on the results of this investigation, the previous observations on the efficiency of confining FRP wraps have confirmed. More specifically, the following concluding remark can be made.

- The observed results indicates that the external confinement using Glass Fibre Reinforced Polymer (GFRP) enhances the mechanical properties of Reinforced Concrete specimens, in different amount according to the FRP type, concrete properties and cross-section shape
- The efficiency of GFRP confinement is higher for circular columns than for square sections, as expected. The increase of ultimate strength of sharp edged sections is low, although there is a certain gain of load capacity and ductility.
- The failure GFRP confined specimens occurred in a sudden and explosive way preceded by typical creeping sounds. For cylindrical specimens, the fibre rupture starts mainly in their central zone, then propagates towards other sections. Regarding confined concrete square columns, failure initiated at or near a corner, because of the high stress concentration at these locations
- The GFRP confinement on Normal-strength concrete specimens produced higher results in terms of strength and ductility than for high strength concrete similar specimens. For example, WR wrapped normal strength concrete specimen with 50mm corner radius shows a gain of 26.5% whereas High strength WR wrapped specimen yields only 26.5% Therefore the effect of GFRP confinement on the bearing and deformation capacities decreases with increasing concrete strength.
- Comparing with Chopped Strand Mat (CSM) GFRP wrap type, Woven Roving (WR) type shows better result in which square specimen with CSM wrap gains 121% of stress whereas WR wrap gains 125%. For Cylindrical column with CSM and WR the gain is 122% and 129% respectively.
- For Normal strength concrete, Woven roving Confinement accompanied by cornering of Square sections enhances the performance in terms of concrete strength and ductility. The larger the corner radius, the greater the increase in efficiency. The square columns with 50mm corner radius yields a better result by showing 125% of stress gain when compared with unconfined specimen, whereas specimen with 15mm corner radius gains 43.6% . In case of cylindrical column the gain is 129%. From which, it is evident that cornering of square column enhances the efficiency, in which this gain in efficiency approximately similar to cylindrical column.
- External confinement using GFRP composite is more effective than reinforcing bars

Thus it is easily concluded that (1)external confinement using shape modification enhances efficiency (2)whereas Woven Roving (WR) wrap yields better performance than Chopped Strand Mat (CSM). (3)The optimized concrete mix for external confinement is Normal-strength concrete mix

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