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Compressive behavior of galvanized steel wire mesh (GSWM) strengthened RC short column of varying shapes

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Abstract. In a reinforced concrete building different shapes of column are adopted depending on the structural orientation and the architectural aspect. When there is an increase in loading due to changes in usage or revision in the design codes these columns need to be strengthened for enhanced performance during their service life. Strengthening materials such as carbon fiber and glass fiber polymer has been successfully used however, due to high cost application other alternative materials need to be explore. Galvanized steel wire mesh (GSWM) is one of the suitable materials locally available. High tensile strength, low weight, corrosion resistance, easy installation, minimum change in dimensions of the sections and cost effectives are the advantages of GSWM. Therefore, in this paper, four different shapes of column such as circular, square, rectangular and L were wrapped with different layers GSWM and jacketed with mortar. All the specimens were tested under axial compression. The objective of the study is to investigate the effectiveness of GSWM as a confining material for strengthening of column having varying shape. Test results shows that the axial strength enhanced with wrapping of GSWM jacket and a circular column presented the highest load carrying capacity and ductility as compared to the others. From the study of 22 column specimens, it is found that axial load is increased upto 20% and 19% when circular and square column are strengthened with one wrap of GSWM respectively, while a rectangular and L column required a wraps of two and three layers respectively in order to achieved the same load capacity as that of a circular column. Based on the present study, it is concluded that GSWM can be effectively used for strengthening of different shapes of concrete columns economically.

Keywords: axial strengthening; column of varying shapes; Galvanized steel wire mesh; load-displacement

1. Introduction

Column of varying shapes has been found in many old and new reinforced concrete (RC) buildings. The different shapes of column were adopted due to structural orientation and the architectural aspects as shown in Fig.1. When there is an increase in loading due to changes in usage or revision in the design codes these columns need to be retrofitted for enhanced performance during their service life. During the last few decades, several method of repair and strengthening of concrete structural members have been reported. The external confinement using steel strip (Tarabia and Albakry 2014), steel jacketing (He *et al*. 2016), prestressed steel strips (Zhang *et al*. 2015) showed ability in resisting an extensive applied axial load. The failure in most of the strengthened specimens was due to the original columns. Concrete jacketing (Campione *et al.* 2014) are the most commonly used methods. The analysis showed the effectiveness of the reinforcing technique in improving both

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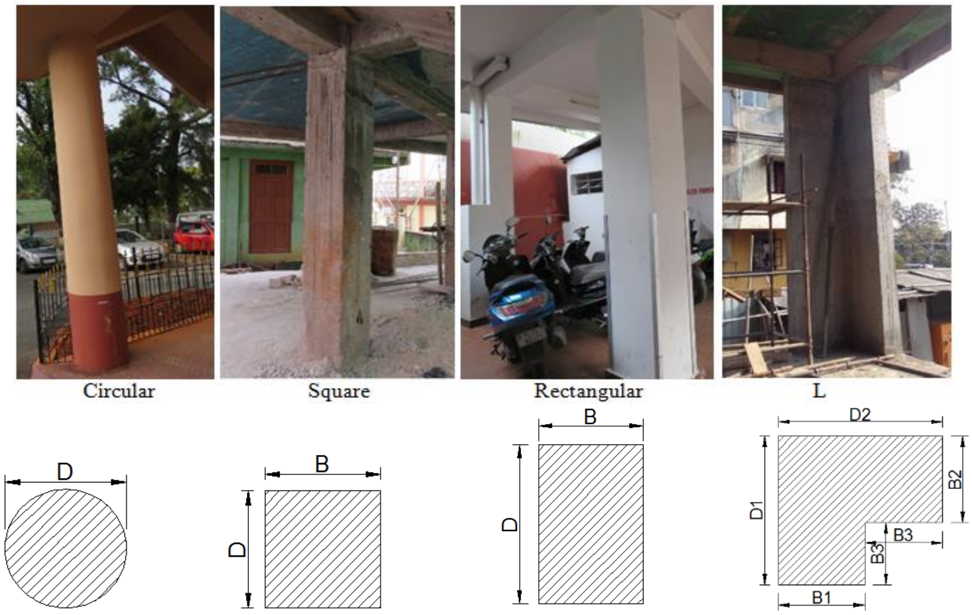


Note: B & D are the dimension of the corresponding depth and width of the sections

Fig. 1 Shapes of column

the strength and the ductility of RC cross-sections of columns (Habib *et al.* 2020). However, these techniques possess its own practical limitations like labour intensive, artful detailing, increased dimension of structural element, susceptibility to corrosion etc. To overcome the difficulties associated with these techniques recent research efforts have focused on the use of epoxy-bonded fiber-reinforced polymer (FRP). This technique eliminates many of the previously mentioned limitations that concrete and steel jacketing possess. The effectiveness of FRP composite jackets for enhanced the compressive strength and ductility of concrete columns has been theoretical and experimental proved in many of the studies; for example, Parvin and Wang (2001), Cheng *et al.* (2002), Hodhod *et al.* (2005), Hadi (2007), Campione (2008), Elwan and Rashed (2011), Narmashiri and Mehramiz (2016), Chen and Ozbakkaloglu (2016), Vuggumudi and Alagusundaramoorthy (2018), Afshin *et al.* (2019), Sarafraz (2019), Yoddumrong *et al.* (2020), Hwang *et al.* (2020). Further, the employ of hybrid NSM reinforced and FRP confined short RC columns under axial compression were reported to be more efficient leading to higher increase in strength, stiffness and ductility as compared to only NSM strengthened or only CFRP confined RC columns (Chellapandian *et al.* 2017). Although the use of FRP composites jackets enhanced the compressive strength and ductility of concrete columns the anchoring of FRP materials however, has evolved as a difficult problem for the effectiveness of this technique (Ghobarah *et al.* 2002). In addition to FRP, composite grid (Bentayeb 2007) and textile (Ortlepp and Ortlepp 2017) has also been used as strengthening method to improve strength and ductility of concrete columns. However, owing to the high manufacturing and application costs of these materials, the need to investigate other possible wrapping materials has arisen.

Alternative to FRP and composite grid, Choi (2008) and Kumar and Patel (2016a, b) used stainless steel wire mesh (SSWM) as a strengthening material to increase the axial strength and ductility of concrete column. Kumar and Patel (2016a, b) observed an increase of axial strength upto 61% and 86% when a circular column was strengthened with one and two wraps of SSWM. Apart from having high tensile strength, high modulus of elasticity, low weight, corrosion resistance the easy installation, minimum change in dimensions of the sections and cost effectives are the advantages of SSWM. Galvanized steel wire mesh (GSWM) is another type of material which has properties like those of SSWM, these materials is locally available and cheaper than SSWM. The effectiveness of using GSSM as a confining material for strengthening of column has been investigated by Hadi and Zhau (2011). They concluded that considerable increases in strength and ductility of concrete members can be achieved at modest costs. The application of GSSM as a confining material for strengthening of structural members were also reported by Marthong (2019 a, b). The seismic capacity of the damaged RC beam-column connections/joints were successfully restored using GSWM as a confining materials embedded with mortar. Therefore, in this investigation, locally available galvanized steel wire mesh (GSWM) has been used as the wrapping materials for confinement of concrete column of varying shapes for axial strength enhancement.

As govern by the structural orientation of framing beams (i.e spans of beams that connected a particular column) and the architectural aspect, different types of column configurations are adopted in many of the RC building. Strengthening of circular column (Kumar and Patel 2016a, b, Narmashiri and Mehramiz 2016) and square column (Kaish *et al.* 2012, Kaish *et al*. 2016) using wire mesh are mostly adopted. It is known that in case of strengthened column, the circular column gave the best performance among the other shapes due to less stress concentration and ability to give a full confinement. An improvement in stress concentration has been address by Kaish *et al*. (2012), where the sharp corners of square column is rounded and provided with an extra mesh layers, which help in pushing the stresses from corner to the core concrete and thus improved the performance of the column subjected to concentric or eccentric loads. To the author knowledge, less study considered all four types of shapes of column strengthened with GSWM. Raval and Dave (2013) is the only comparative study that considered three different shapes of column such as circular, square and rectangular strengthened with FRP. Therefore, the objective of the present study is to investigate the effectiveness of GSWM as a confining material for strengthening of column having varying shape. The strengthening procedure is very simple and required no skilled man force hence it would be helpful to the construction industry in strengthening of existing deficient RC column for future used. Further, it can also be employed for repairing of the damaged RC column for post earthquake usage.

There are varieties of GSWM locally available depending on the thickness of wires and grid opening in which the costs vary from 120 per m^2 to 220 per m^2. The present study used a GSWM which has a grid size of 25 x 25 mm and 1.2 mm thick wire.

2. Experimental program

The experimental study was carried out on RC short column of four different shapes as shown in Fig. 2. The RC column were design as per IS: 456 (2000). The height of the specimens was kept as 600 mm and the shapes were varied like (a) Circular (b) Square (c) Rectangular and (d) L. All these columns were treated as reference specimens. Another similar set of RC columns were casted and wrapped with GSWM jacket. In order to maintain the same cross sectional area for reference

Table 1 Detail of non-jacketed and GSWM jacketed specimens

Specimen shapes	Designation of column	Specimen sizes excluding the GSWM jacket (mm)			Original cross-sectional area (mm^2)	Reinforcement	Thickness of jacket (mm)	Type of GSWM jacket
		Breadth (mm)	Width (mm)	Height (mm)				
Circular	C0	140Ø	-	600	15393.80	(a) Main Bars: 6# 6 mm Ø (b) Stirrups: 6 mm Ø @ 100 mm c/c	12.5	Plain mortar jacketed
	C1	140Ø	-	600	15393.80		12.5	One layer of GSWM jacket
Square	S0	125	125	600	15625.00	(a) Main Bars:4# 6 mm Ø (b) Stirrups: 6 mm Ø @ 100 mm c/c	12.5	Plain mortar jacketed
	S1	125	125	600	15625.00		12.5	One layer of GSWM jacket
Rectangular	R0	110	140	600	15400.00	(a) Main Bars:4# 6 mm Ø (b) Stirrups: 6 mm Ø @ 100 mm c/c	12.5	Plain mortar jacketed
	R1 and R2	110	140	600	15400.00		12.5	One and two layers of GSWM jacket
L	L0	160 80	80 80	600	19200.00	(a) Main Bars:8# 6 mm Ø (b) Stirrups: 6 mm Ø @ 100 mm c/c	12.5	Plain mortar jacketed
	L1, L2, L3	160 80	80 80	600	19200.00		12.5	One , two and three layers of GSWM jacket

and GSWM jacket specimens. The reference specimens were also jacketed with plain mortar mix without GSWM. The GSWM column consisted of a single GSWM layer for a circular and square column, while a double layers for rectangular and a triple layers for an L column. In general, circular column with plain mortar jacketed are designated as C0 and when wrapped with one layer GSWM are designated as C1. Similarly, square, rectangular and L shape plain mortar jacketed column are designated as S0, R0 and L0. Circular and square column wrapped with one layer of GSWM are named as C1 and S1. For a rectangular column of one and two layers are designated as R1 and R2 and for L column with one, two and three layers of GSWM are designated as L1, L2 and L3 respectively. The detail description of the specimens is shown in Table 1.

2.1 Materials for test specimens

2.1.1 Cement and aggregates

Ordinary Portland Cement (OPC) of 53 grades conforming to IS: 12269 (2013) was considered. The maximum size of coarse aggregate was 12.5 mm. River sand was used as fine aggregate. Aggregates used have been tested as per relevant codes (IS: 2386a & b, 1963).

2.1.2 Galvanized steel wire mesh (GSWM)

Galvanized steel wire mesh (GSWM) as shown in Fig. 3 was used in this study. The opening of the mesh (grid size) was 25 mm square. The diameter of wires in the mesh was 1.2 mm. The GSWM locally available were procured in the form of rolls of 1 m wide and then cut as per required size. The yield strength of individual wires of the mesh was 300 MPa tested as per standard guidelines of ACI Committee 549 (2008).

2.2 Mix design

2.2.1 Concrete mix

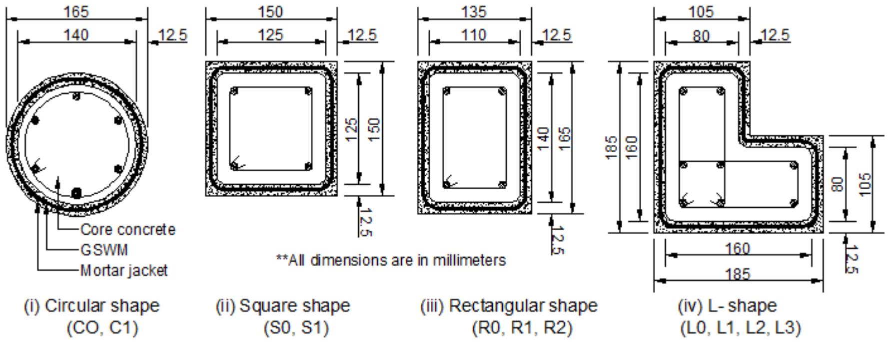
Concrete mix was designed for a characteristic cube compressive strength of 25 MPa which resulted in a target mean cube compressive strength of 31.6 MPa as per Indian Standard IS: 10262 (2009) code provisions. All concrete mixes were produced with 383 kg/m^3 of cement, 720 kg/m^3 of fine aggregate, 1100 kg/m^3 of coarse aggregate, for a water-cement ratio of 0.5 and a compaction factor of 0.9. The cement concrete cubes 150 mm x 150 mm x 150 mm were casted for compressive strength determination. Specimens were demoulded after 24 hours of casting and were kept in the water tank for 28 days curing period. The compressive strength after 28 days was recorded as 33.16 MPa.

2.2.2. Jacketing material

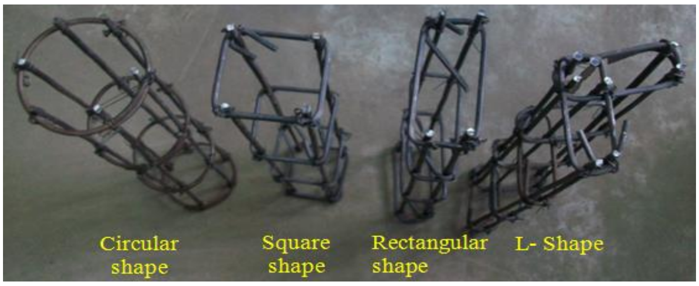
The mix proportion of mortar was 1:2 by weight of cement and sand, respectively. The water to cement ratio was 0.45. The compressive strength of mortar cube was 20.23 Mpa and 32.65 MPa at 7 and 28 days of curing respectively.

2.2.3 Bonding agent

For attaining adequate bond between newly added cementitious materials to existing concrete surfaces a suitable bonding agent was applied. The bonding agent is based on solvent free epoxy resins containing pigments and fine fillers. The bonding agent has been designed with an overlay time of 10 hrs at 20 ºC and 6 hrs at 30 ºC making it more suitable for use where additional reinforcing bars and formwork has to be fitted. As per manufacturer data sheet the compressive and tensile strength at 7 days are 50 N/mm^2 and 26 N/mm^2 respectively.



(a) Shapes section of test specimens



(b) Reinforcement detailing

Fig. 2 Details of test specimens

2.3 Mixing and casting procedures of RC column specimens

The reinforcement detailing and dimensions of different shape of RC column is shown in Fig. 2(b) and Table 1. The cross sectional area of L shape column is 20% higher than those of other column. Higher cross sectional area of L-shape column was adopted for easy placement of reinforcement inside the molds. Totally, 22 column specimens were casted with 2 on each type of GSWM jacket. A mild steel bar of 6 mm diameter was used as a longitudinal and transverse reinforcement. The vertical spacing of the transverse reinforcement is 100mm center to center. Aluminum sheets and wooden molds of required size and shape were used for casting of column specimens. All specimens were casted in the vertical directions. Before casting the molds was properly oiled and concrete mix was prepared according to the mix design and placed into the molds. To achieve the same strength of concrete, all specimens were casted from the same batch of concrete mix. A concrete mixer was used for mixing the ingredients with water. Workability of concrete was checked by slump test. Slump values were found approximately as 80 mm. Because of the smaller size of specimens considered in this study, a hand compaction using a 6 mm diameter steel rod was used. Three companion concrete cube of size 150 mm were also casted to determine the ultimate compressive strength of the concrete mix. All casted specimens were de-molded after 24 h from their time of casting and placed them into the water for 14 days for proper curing.

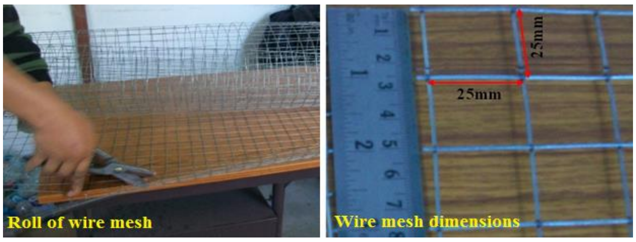
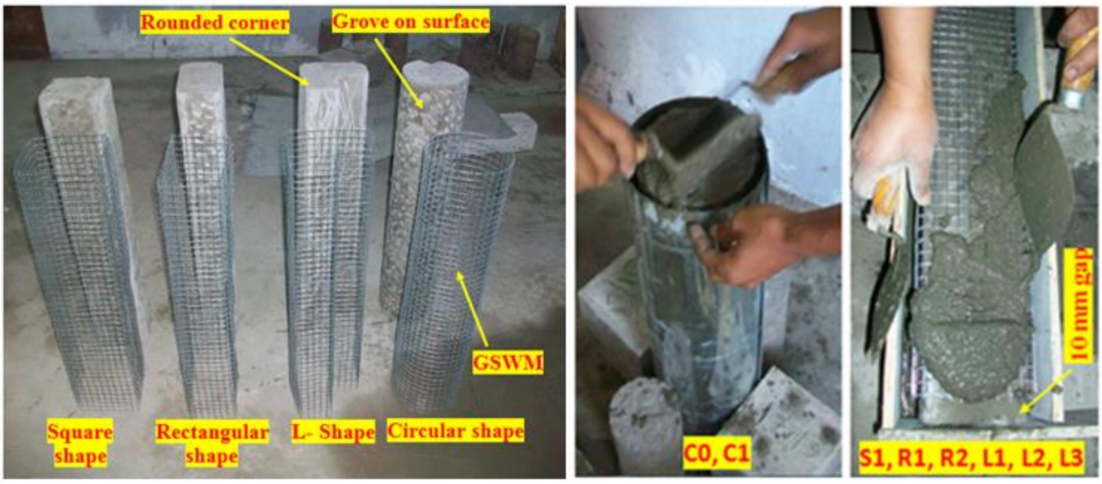


Fig. 3 GSWM materials

2.4 Preparation of plain and GSWM jacket for column strengthening

The concrete specimens were jacketed with plain mortar and GSWM after 14 days of concrete casting. Sharp corner of square, rectangular and L shape columns were rounded for reducing stress concentration at the corner before placing of GSWM. Further, the surface of specimens was randomly cut into small grove using circular saw to increase the bonding of the freshly added mortar mix with the old concrete surface. Bonding agent was also applied on the surface of the existing column prior to wrapping with GSWM and mortar jacketed to achieved a proper bond. Fig. 4 presented the casting procedure of jacketed specimens. Circular column were casted in vertical position, while the other three column types were casted in horizontal position. The joints of the GSWM were secured at different locations together using double thin steel wires that are commonly used in tying reinforcing bars. The required GSWM was placed at the middle section of the jacket with a clear cover of 6 mm for jacketing of circular column. A circular aluminum sheet was then placed around the circular specimen for placing the mortar. The diameter of the circular aluminum sheet was 25 mm more than the diameter of circular column. This circular aluminum sheet was used in order to get a constant thickness of wrapping throughout the height of the specimens. After that the mortar was placed into the round aluminum sheet. Square, rectangular and L shape column were casted in different way. At first, 6 mm thick mix mortar of mixing ratio of 1:2 (cement: sand) by weight was placed on the exterior surface of the column specimens then wire mesh was wrapped around the columns. Thereafter, all the specimens were plastered about 6 mm thick with the same proportioned mix mortar. A small gap of 10 mm of GSWM was kept between RC column specimen and jacket at both the top and bottom of the specimen to avoid direct compression on the jacket. After jacketing the dimension of the GSWM specimens was increase as compared to those of the reference specimens. It is expected that due to the increase in dimensions of the jacketed column, the axial compressive strength as well as the enhancement of confining pressure increases. In addition, the stiffness and energy absorption capacity also increase due to the larger dimensions. The above mentioned parameters may not achieve by the reference specimens due to the lesser cross-sectional area. Therefore, to maintain the same cross sectional area all reference specimens were also jacketed with plain cement mortar mix. This concept was adopted from the work of Kondraivendhan and Pradhan (2009). This casting procedure was adopted for facilitating comparative understanding of their behaviour. All columns were jacketed from the same batch of mortar mix. The final cross-section of jacketed specimens is presented in Table 1. After completing, jacketed specimens were cured in the water for 28 days from the date of jacketing of column specimen.



(a) Surface preparation (b) Installation of GSWM jacket

Fig. 4 Casting of specimens

2.5 Testing procedure and instrumentation

The compressive strength test was carried out in accordance to IS: 516 (1959). All the specimens were tested in a 1000 KN capacity universal testing machine (UTM). The specimen was placed vertically on the floor of the machine and tested under monotonically increasing compressive load. The load and axial displacement was recorded by an in-built load cell and linear-variable differential transformer (LVDT) for measuring force and displacement. Lateral deformation was measured by a dial gauges with an accuracy of 0.01 mm place laterally at the mid height of the column specimen. The test setup and actual testing of specimen is shown in Fig. 5.

3. Results and discussion

The experiment was conducted in three stages. At first, eight specimens of two in each shaped were casted. Out of these eight specimens one specimen each was jacketed with plain mortar and another by wrapping with one layer of GSWM and then tested. Parameters like ultimate load, axial and lateral deformations, stiffness and ductility of reference and GSWM jacketed specimens were evaluated and compared for ascertaining the effectiveness of GSWM as a confining material. Circular (C1) and square column (S1) showed a better performance as compared to C0 and S0 in term of the above mentioned parameters in comparison to rectangular (R1) and L (L1) shaped column. Therefore, in the next stage two specimens of rectangular and L shaped column each were casted and wrapped with two layers of GSWM and then tested. With the two layers of GSWM wrapping the rectangular column (R2) showed adequate performance, while L2 column is still not satisfactory. Hence, in the last stage one more L shaped column was casted and again wrapped with three layers of GSWM and named as L3 and then tested.

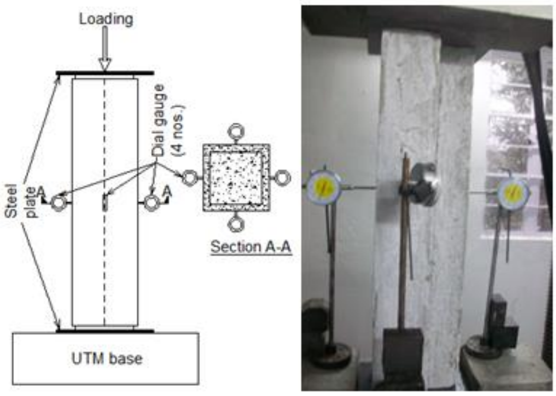


Fig. 5 Testing of specimens

3.1 Failure mode of jacketed specimens

Fig. 6 presented a typical failure pattern of the plain and GSWM jacketed specimens. It is observed that the failure of the all specimens (reference and GSWM jacketed) was mainly initiated by the formation of hairline cracks. The crack width increases with the increase of the applied loads. However, in the case of reference specimens, once the crack width increased the mortar jacket delaminated from the concrete column surface and there after crushing of concrete column starts. On opening the mortar jacket it was observed that the longitudinal reinforcement also buckled. The buckled reinforcement is found to be significant for the L-shaped column. On the other hand, the failure of GSWM jacketed specimens was mainly due to the failure of GSWM and the crushing of concrete as well as the buckling of longitudinal reinforcement is of lesser magnitude except for rectangular and L shaped column. The rectangular (R1) and L (L1) shaped column confined with a single layer of GSWM showed a catastrophic failure together with the disintegration of external jacket and the concrete core. This disintegration is more prominent for L shaped column. However, the two and three layers of GSWM for a rectangular (R2) and L (L3) shaped column did not show the disintegration of GSWM jacket and the concrete core as well. Vertical crack was also observed throughout the height of the confining jacket in these types of specimens regardless of the shapes of specimens. Conclusively, due to the slenderness effect the rectangular and L shaped column required a two and three wrapping of GSWM in order to achieve an effective confinement of core concrete as compared to a circular and square column.

3.2 Ultimate load carrying capacity

The load carrying capacity of all columns is presented in Table 2. Circular columns exhibited higher axial load carrying capacity as compared to that of the others. Axial load carrying capacity increases from L shaped column to circular columns. L shaped column exhibits lowest axial load carrying capacity. Results clearly demonstrated that variation in shaped plays a significant role in increasing the amount of axial load carrying capacity for RC columns. The change of shaped from circular to square, rectangular and L shaped causes a strength reduction of 5%, 18% and 20% respectively for control specimens. The effectiveness of confined layers was observed in the case of circular column. Circular column gives full confinement and therefore has resulted in to attainment

(a) One layer GSWM (b) Two and three layers of GSWM

Fig. 6 Failure of tested specimens

of the highest compressive strength. As shown in Fig. 7 a single layer mesh confinement for a column C1 led to an increase in the load carrying capacity upto 20%. It may be mentioned that before installation of GSWM the sharp corners of all the columns has been rounded for reducing the stress concentration resulted at the corners (Kaish *et al.* 2012, Chen and Ozbakkaloglu 2016). Due to these treatments and because of uniform in dimensions, a single layer GSWM confinement is sufficient for a square column (S1) to increase the load carrying capacity to 19%. On the other hand, a single layer GSWM confinement for a rectangular (R1) and L (L1) column led to an increase in load carrying capacity of only 11% and 6% respectively, which is not sufficient as compared to 20% increased in the circular column (C1). Therefore, in order to enhanced the axial load capacity of a rectangular and L shaped column it is necessary to increase the number of GSWM wrapped layers from one to two layers each. On increasing the GSWM wraps it was observed that the load carrying capacity of a rectangular (R2) and L (L2) column was 19% and 13% respectively. From this performance it is concluded that rectangular column required two layers of GSWM wrapping in order to achieve the same levels of load capacity as those of circular column (C1). In the other hand the L shaped column however, could not sufficiently achieved the similar load capacity with two layers GSWM wrapping. However, on increasing the mesh layers from two to three for an L shaped column the load carrying capacity of L3 column enhanced to about 18%. From the results on various stages of strengthening it may be concluded that GSWM is an effective materials for increasing the load carrying capacity of RC column. However, for achieving the desired load carrying capacity of column having varying shapes the number of mesh layers plays a significant role.

3.3 Load versus deformation response

Figs. 8(a)-8(c) presented the axial load versus deformation behavior for all columns. It is seen that, all GSWM wrapped column shows higher axial deformation than the reference specimens at the ultimate loads. The effect of geometry as well as effect of GSWM wrapping on load versus

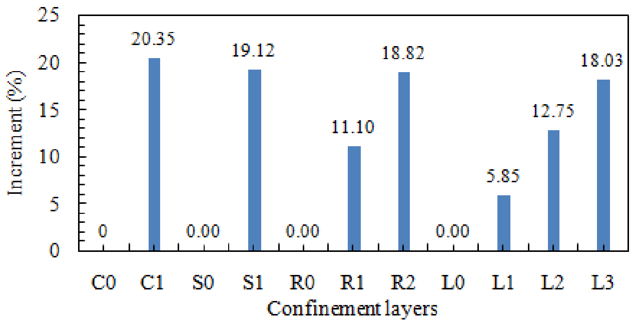


Fig. 7 Percent increment in ultimate load of various jacketed column with respect to confinement layers

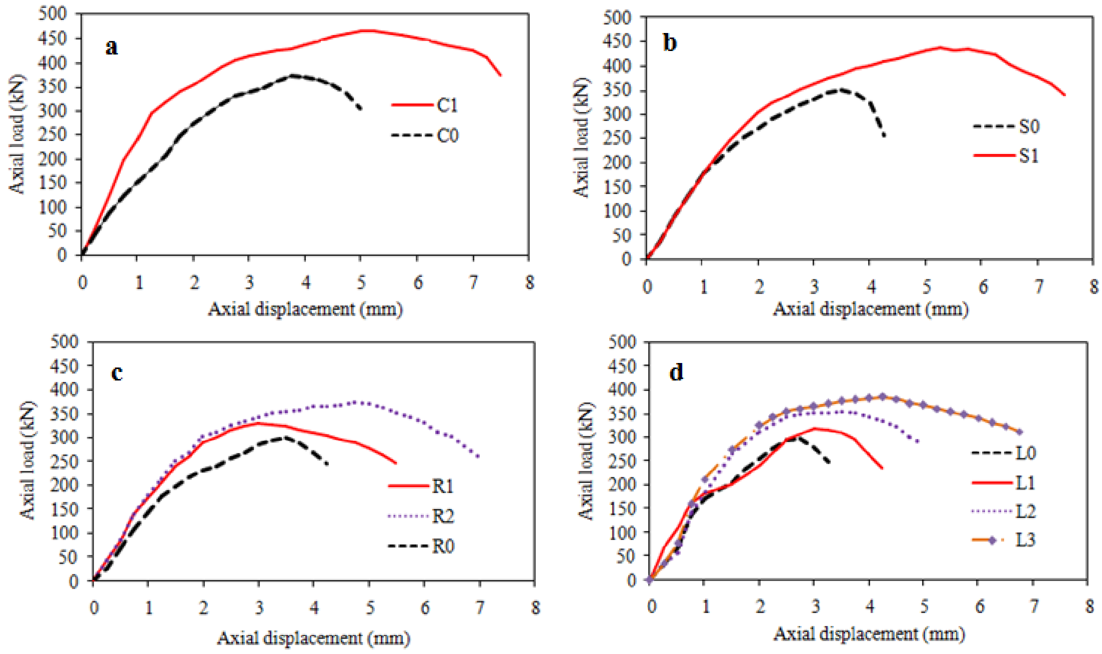


Fig . 8 Load versus deformation behavior of column

deformation are exhibited in Fig. 8. For one layer wrapping column C1 also show higher load carrying capacity with increase in deformation and ultimate load as compared to the column of other shapes. Circular column gives full confinement and therefore has resulted in a ductile failure of geometry is clearly seen in case of a rectangular and L shaped column, which show load-deformation behaviour similar to a reference specimens (C0 and S0). The GSWM wraps of two and three layers for a rectangular (R2) and L (L3) column however, increased the load carrying capacity of the specimens and hence resulted an improved load-deformation characteristics, which is similar to the C1 and S1column.

3.4 Stiffness degradation

Stiffness is an indicator of the response of a specimen and extent of strength degradation during loading. It is calculated as the slope of the line joining the peak capacity at a given displacement. The slope of this straight line is the stiffness *(K)* of the specimens corresponding to that particular displacement and is calculated by the following expression as recommended by Naeim and Kelly (1999).

$$K = \frac{F_D^+ - F_D^-}{D_D^+ - D_D^-} \tag{1}$$

where F_D^+ and F_D^- D_D^+ and D_D^- in Eq. (1) are the positive and negative loads and the corresponding displacements in case of cyclic loading. In the present study both negative loads and displacement is taken as zero due to monotonic load application. The effectiveness of GSWM as a confining material for strengthening of column may be evaluated by comparing stiffness vs. displacement for different column types. These plots for all the specimens are shown in Fig. 9. Comparing these curves (reference and strengthened) irrespective of column types, similar degradations trends could be observed. However, initial stiffness of all GSWM jacketed specimens consistently shows higher values than those of reference specimens and being highest for a circular column, which may be attributed to the confined effect due to GSWM jacket. Wrapping with one layer of GSWM led to an increase in the initial stiffness of a circular and square column upto 30% and 28% respectively, while the increase of wraps layers from one to two and two to three for a rectangular and L column further improve the initial stiffness upto 27% and 34% respectively.

3.5 Displacement ductility

Ductility is basically the ability of a structure to accommodate deformations well beyond the elastic limit. It is the capacity to dissipate energy in hysteretic loops and to sustain large deformations. As the loads versus displacement curves for tested specimens do not have a distinct yield point, ductility capacity was determined using an idealized approximation procedure proposed by Shannag *et al.* (2005) which has been explained in Fig. 10. As shown in the figure, the yield displacement is calculated as the point of intersection between two straight lines drawn in the envelope curve. The first line was obtained by extending the line joining the origin and 50 % of ultimate load capacity point of the curve, while the second line was obtained by drawing a horizontal line through the 80 % of ultimate load capacity point. In the figure, δy represent the yield displacement. Horizontal lines drawn through the 80% of ultimate load capacity point intersect the curve at far end at points *x*. The abscissa of this point denoted by δu was taken as maximum displacement. The displacement ductility (μ) was calculated as the ratio of maximum displacement (δu) to the yield displacement (δy). The calculated values listed in Table 3 clearly show a higher ductility was achieved in case of GSWM column as compared to the reference specimens, which proved the efficacy of GSWM as a confining material. Out of the four columns the ductility increases from an L to circular column, which clearly demonstrated the effect of geometry under axial compression. However, this can be compensated by increasing the GSWM wrapped layers i.e two and three layers respectively for a rectangular and an L column.

Table 2 Load carrying capacity the tested specimens

Specimen	One layer confinement		Two layers confinement		Three layers confinement	
	Ultimate load (KN)	Increase of strength with one layer confinement (%)	Ultimate load (KN)	Increase of strength with two layer confinement (%)	Ultimate load (KN)	Increase of strength with three layer confinement (%)
C0	370.99	-	-	-	-	-
C1	465.79	20.35	-	-	-	-
S0	351.75	-	-	-	-	-
S1	434.88	19.16	-	-	-	-
R0	305.52	-	-	-	-	-
R1	343.68	11.10	-	-	-	-
R2	-	-	376.34	18.82	-	-
L0	297.28	-	-	-	-	-
L1	315.74	5.85	-	-	-	-
L2	-	-	361.89	12.75	-	-
L3	-	-	-	-	385.18	18.03

Table 3 Displacement ductility and energy absorption capacity of specimens

Specimens	Ductility ($\delta = \delta y/\delta u$)	Energy absorption (KN-mm)
C0	2.70	1308.21
C1	3.52	2901.1
S0	2.57	1029.5
S1	3.26	2179.9
R0	2.48	873.06
R1	3.08	1383.2
R2	3.32	2051.5
L0	2.50	646.09
L1	2.96	928.45
L2	3.25	1345.5
L3	4.05	2009.1

3.6 Absorbed energy before failure

The ability of a structural member to resist the fracture when subjected to static or to dynamic or impact loads depends to a large extent on its capacity to dissipate its energy. Hadi (2007) reported

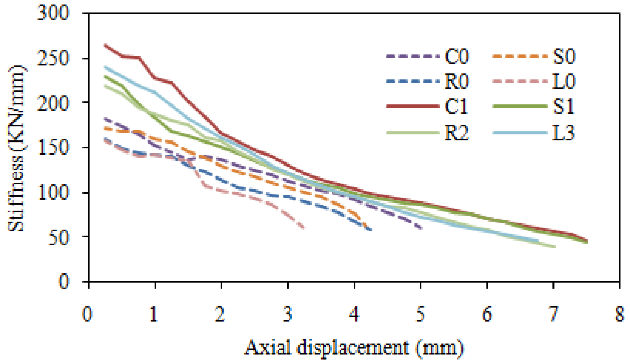


Fig. 9 Variation of stiffness

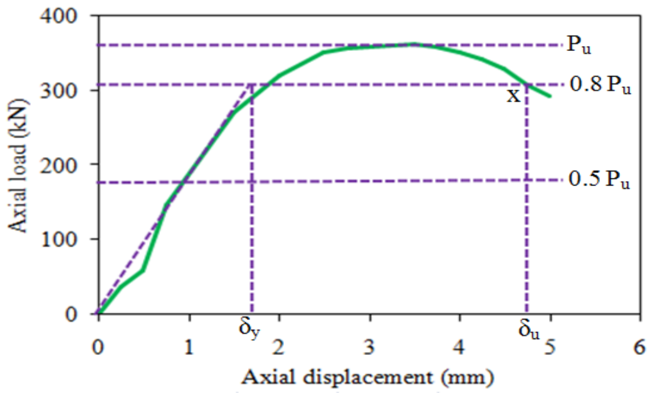


Fig. 10 Procedures for ductility calculation

that the energy absorbed by a column before failure is correlated to the ductility of the column. This energy can be computed based on the area under the axial load versus axial deflection curve presented in Fig. 7 as implemented in several previous studies by Hadi (2006), Hadi (2007), and Shannag and Ziyyad (2007). The computed energies are tabulated in Table 3. These values indicate that the maximum energy was absorbed by the GSWM specimens, which shows the efficacy of the confining materials. For one GSWM wrapped layer the energy absorbed by C1, S1, R1 and L1 are 2.22, 2.12, 1.58 and 1.44 times respectively as compared to the reference specimens. However, it may be worth mentioning that the efficacy of the confining materials depends on the geometry of the specimens. Rectangular and L shaped column presented lower energy dissipation as compared to circular and square column and the energy dissipation increases from L shaped column to circular. However, the energy dissipation can be improved by increasing the GSWM wrapped layers.

3.7 Effect of shape

The effect of variation in shape for different columns have been studied and examined. The ratio ($f'cc / fcc$) of GSWM confined concrete is defined as the ratio of the confining strength ($f'cc$)

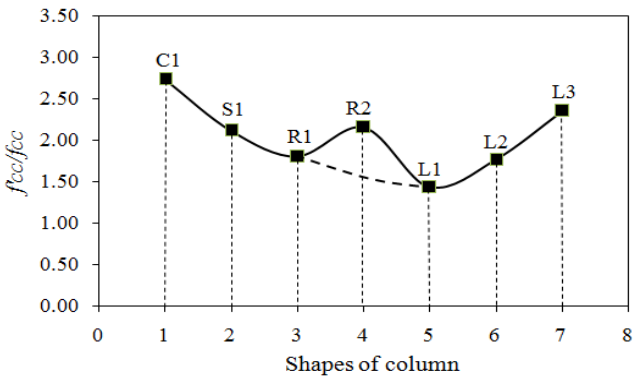


Fig. 11 Effect of variation in shapes on confinement

to the unconfined concrete strength (fcc). Confinement ratio measures how effectively the concrete is confined for a given shape of column. It can be observed from Fig. 11. That with the change in shape for the column from circular to L, the confinement ratio decrease. Circular GSWM wrapped column shows the best confinement as compared to that of other columns. Confinement by GSWM enhances the performance of circular columns much better as compared to that of square, rectangular and L columns. Further, it is also observed that confinement ratio of columns having irregularity in dimensions can be increased with increasing GSWM wraps layers accordingly, which indicated the effectiveness GSWM as a confining materials.

4. Conclusions

Based on the experimental results, the following conclusions are drawn:

1. Load carrying capacity and ductility of column decreases with varying in shapes from circular to L column.
2. The GSWM which is locally available can be used for structural strengthening of all the four types of column. However, for rectangular and L column the effectiveness of the GSWM as a confining material depend on the number of wrapped layers. For, a circular and square column, a one wrapped layer is sufficient to increase the axial load carrying capacity to 20% approximately, while for rectangular and L column it is required to wrap two and three layers respectively to achieve the same load capacity as that of a circular column.
3. Irrespective to the shape of column when there is an increase in loading due to changes in usage or revision in the design codes columns need to be strengthened for enhancement their performance during their service life. The present study suggested that application of GSWM for strengthening of these columns proved to be viable.
4. The study used one type of GSWM. Various types of meshes are locally available. A similar study on column strengthening may be carried out by adopting different mesh type and the best may be recommended.
5. Short columns subjected to axial compression only are considered in the present study. Short column are rare in the real application hence further study may be extend to long column with eccentric loading condition for acceptability of the results.

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