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Improved confinement of reinforced concrete columns

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Abstract Traditional steel ties reinforcement cannot provide superior confinement for reinforced concrete (RC) columns due to the constraints on tie spacing and disturbance of concrete continuity. This paper presents a practical confinement configuration consisting of single Expanded Metal Mesh (EMM) layer in additional to regular tie reinforcement. The EMM layer is warped above ties. The proposed transverse reinforcement, with various volumetric ratios of ties, was investigated in sixteen square short RC column specimens categorized in two groups according to their slenderness ratios. The specimens were cast in vertical position simulating the construction field and they were tested under concentric compression till failure. The results indicated that the columns, confined with proposed lateral reinforcement, revealed significant improvement in the strength and ductility. Also, high reduction in ties volumetric ratio with no loss in ultimate load could be achieved by installing the EMM layer.

1. Introduction

Reinforced concrete (RC) is widely used for construction all over the world. Columns transfer the loads from beams and slabs to foundation. Columns support high compressive forces in mega structures such as long-span structures and tall buildings. Moreover, columns may suffer damage due to overloading and natural disasters such as earthquakes and fires because of the limited strength and ductility of concrete. Failure of one or more columns may lead to the collapse of the structure.

In 1978, Sheikh and Uzumeri revealed that both the strength and ductility of columns are improved by distributing the longitudinal reinforcement bars around the core perimeter and confining these bars with laterals such as ties [1]. Therefore, both longitudinal and lateral reinforcements are

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essential for RC columns. While the concrete core is subjected to radial compression in the horizontal direction, the confining volume is subjected to hoop tension. However, either the large spacing or close spacing between ties results in lack of confinement of concrete core. While low volumetric ratio of ties reduces the confinement of concrete core [2], high volumetric ratio of ties defects concrete continuity and creates a weak plane between the core and the concrete cover [3] besides creating construction problems due to the congestion of column cage with reinforcement. Welded reinforcement grids were used by Saatcioglu and Grira [4] and Kusuma et al. [5] to reduce reinforcement congestion due to overlapping hoops, bends and bend extensions.

The shortage of confinement offered by ties was the motivation for using materials such as Expanded Metal Mesh (EMM), Welded Wire Mesh (WMM) and Fiber Reinforced Polymer (FRP) to confine the concrete core. The more availability, lower cost and less need for advanced installation technique for steel meshes (EMM and WWM) make them predominant in developing countries. Steel meshes encapsulated in thin-wall mortar layer (ferrocement, [6]) were extensively used in repair and rehabilitation of existing concrete columns [2,3,7–11]. The uniform distribution of reinforcement in mortar improves many engineering properties such as the ductility, crack resistance, in-plane strength and durability. Ho et al. [7] strengthened circular plain and RC columns with high performance ferrocement jackets (comprising rendering material and wire mesh). Yaqub et al. [8] tested post-heated square and circular RC columns after repair with ferrocement jackets. Kaish et al. [9] presented untraditional ferrocement jackets for re-strengthening square short columns. Mourad and Shannag [2] investigated the preload effect on RC columns strengthened with ferrocement jackets. Xiong [10] confined the plain concrete columns with ferrocement jackets including steel bars. Abdullah and Takiguchi [11] studied the improved seismic performance of RC columns strengthened with ferrocement.

The researches which investigated the use of steel meshes as lateral reinforcement in constructing new RC columns are limited when compared with others that use ferrocement in repair of RC columns. Most of these researches had mainly focused on using WWM to confine the short concrete cylinders, hollow cylinders and circular columns. Balguru [12] and Singh and Kaushik [13] examined the behavior of plain concrete short cylinders confined with WWM and investigated the casting order; whether casting the cylinder as one unit or casting the cylinder core first and then casting the warping ferrocement layer. Rao and Rao [14] reported the behavior of hollow cylindrical ferrocement specimens under axial compression. Abdou [15] monitored the behavior of both circular and square hollow sections with height of one meter under central line loadings. Shaheen and Hassanen [16] reported the behavior of circular concrete column (diameter = 72 mm and height = 1000 mm) reinforced with various types of reinforcing metallic or non-metallic materials. Regarding using the metal meshes as confining lateral reinforcement in RC square columns, Razvi and Saatcioglu [17] explored the behavior of RC square short columns (cross section = 160 × 160 mm and height = 460 mm) confined with WWM under concentric loading. They proposed various configurations for installing WWM inside the concrete core or between the vertical and tie reinforcements. However, it is not without limitations. High volumetric ratios of ties (ρ = 2.64–1.34%) were used in additional to WWM. The installation of WWM inside the core or between the vertical bars and the ties are practically difficult and the studied columns had very small slenderness ratio (λ = 2.875). Also, EL-Sayed and Shaheen [18] tested only one RC square short columns with lateral reinforcement combined of ties (ρ = 0.30%) and one layer of EMM between longitudinal reinforcement and ties. The column dimensions were 150 × 150 × 1000 mm with λ = 6.67. Again, the installation of metal mesh; either WWM or EMM; in the prescribed order is difficult in construction field. Besides, the effects of volumetric ratio of ties, and slenderness ratio of column were not investigated due to the limited number of specimens.

In this paper, sixteen square short RC column specimens of slenderness ratios λ = 7.33 and 14 were reinforced laterally with various volumetric ratios of ties. The confinement of twelve column specimens was enhanced by warping single EMM layer around the ties. The column specimens were tested under axial compression until failure. The results are compared in terms of ultimate capacity, axial displacement, lateral displacement, ductility, energy absorption and crack propagation. The basic concern of this study is to present better lateral reinforcement by using EMM in combination with ties in

Table 1 Details of tested column specimens.

Group	Phase	Specimen ID	Cross section (mm)	Height (mm)	Slenderness ratio	Reinforcement			
						Vertical bars, grade (360/520)	Lateral confinement		
							Ties, grade (240/350)		EMM
							No.	Volumetric ratio%	
Group1	Phase1	SR*i*T5	150 × 150	1100	7.33	4 Ø 10	5 Ø 6	0.2714	–
	Phase2	SF*i*T5					5 Ø 6	0.2714	One layer
		SF*i*T3					3 Ø 6	0.1629	
		SF*i*T1					1 Ø 6	0.0543	
Group2	Phase1	LR*i*T10	150 × 150	2100	14	4 Ø 10	10 Ø 6	0.2714	–
	Phase2	LF*i*T10					10 Ø 6	0.2714	One layer
		LF*i*T6					6 Ø 6	0.1629	
		LF*i*T3					3 Ø 6	0.0814	

x Ø y indicates x bars (or ties) of diameter y mm.
i = specimen repetition = 1, 2.

practical configuration to enhance the confinement and the performance of RC columns.

2. Experimental program

Sixteen one-third scale square (150 × 150 mm) short RC columns were tested under axial compression in the laboratory of concrete research & material properties in the faculty of engineering at Fayoum University. The columns were divided into two groups according to the slenderness ratio λ as follows; *Group1*: eight column specimens with height $h = 1100$ mm and $\lambda = 7.33$, and *Group2:* eight column specimens with height $h = 2100$ mm and $\lambda = 14$. Every group has two phases as follows; *Phase1*: two identical column specimens (one pair) with only transverse ties of volumetric ratio $\rho = 0.2714\%$ as confining reinforcement, and *Phase2:* six column specimens (three pairs) with combined confining reinforcement consisting of ties with $\rho = 0.0543–0.2714\%$ and single EMM layer warped over the ties. The dimensions, reinforcement details and classification of the tested 16 column specimens are given in Table 1 and shown in Figs. 1 and 2.

2.1. Material properties

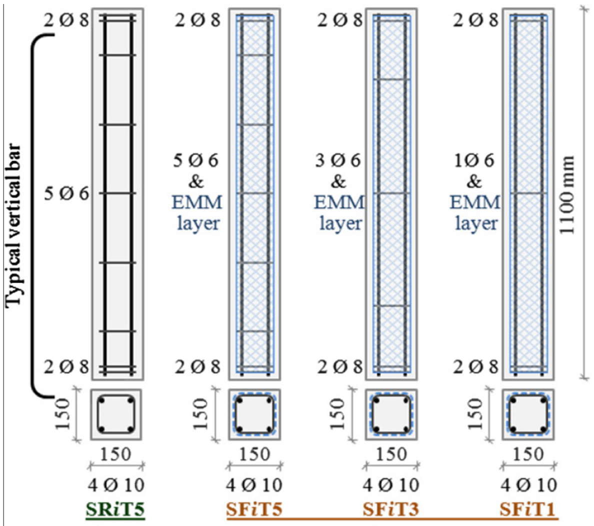
The cement used in preparing the concrete mix is Portland Cement of grade 42.5 MPa conforming type1 (CEM1) of Egyptian Standards (ES) 4756-1/2009 [19] and EN 197-1:2011 [20]. Locally available gravel was sieved on the utilized EMM and then the passed gravel was used as coarse aggregate in the concrete mix. The passed gravel is well graded with maximum size of 16 mm, specific gravity of 2.7 and crushing value of 19.20%. The used fine aggregate is natural siliceous sand of medium size with fineness modulus of 2.49, specific gravity of 2.55 and percentage of clay and other fine materials of 1.70%. Both coarse and fine aggregates conform the ES 1109/2008 [21]. The longitudinal reinforcement used in test specimens is high grade steel with grade 360/520 (yield stress/ultimate stress, MPa) whereas the ties were formed from mild steel with grade 240/350. Horizontal and vertical reinforcements conform ES 262-1/2009 [22] and ES 262-2/2009 [23], respectively. Typical EMM sheets of size 1 × 10 m weighting 13 kg per sheet were used. The mesh has diamond opening with size 16 × 31 mm and strand dimensions 1.25 × 1.5 mm. The specific gravity is 6.4. The proof stress and ultimate stress are 199 MPa and 320 MPa respectively. The gravel was washed by tap water before mixing. The concrete mix comprised cement 375 kg/m^3, fresh water 165 kg/m^3, sand 600 kg/m^3 and gravel 1,111 kg/m^3. The average compressive strength was 368 kg/cm^2, for standard 150 × 150 × 150 mm cubes, on the day of testing the columns. The characteristics of all used materials satisfy the Egyptian code for design and construction of concrete structures (ECP 203/2010) [24].

2.2. Preparation of the specimens

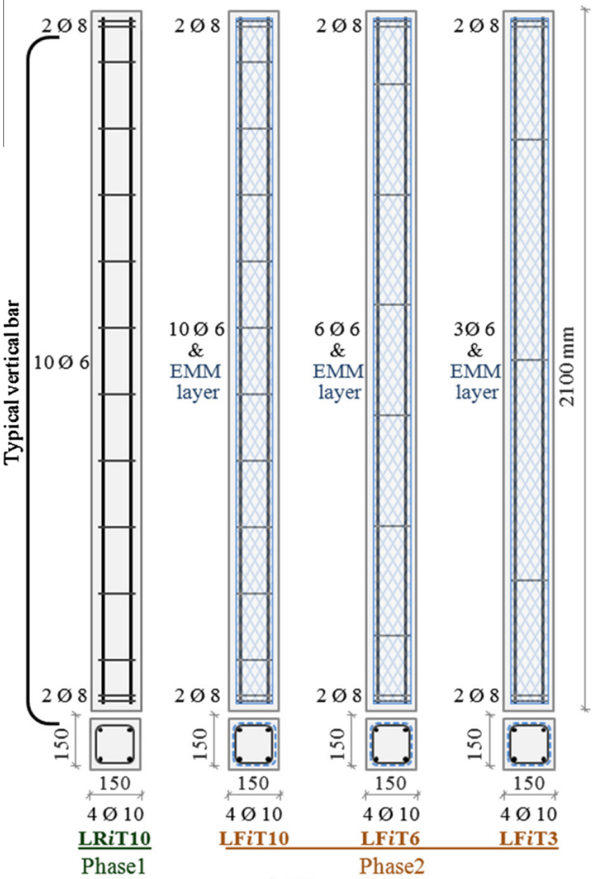
The column specimens were prepared according to the following procedure.

2.2.1. Reinforcement

Four vertical bars of 10 mm diameter were used for the vertical reinforcement. Every pair of column specimens has distinguished lateral reinforcement as given in Table 1 and shown in Figs. 1 and 2. The clear cover was adjusted to 16 mm. Premature load failure at column specimen ends was eliminated by the following precautions: (1) The ends of the vertical bars were flexed horizontally so that both concrete



(a) Group1



(b) Group2

Figure 1 Dimensions and reinforcement details of tested column specimens.

(a) Group1

(b) Group2

Figure 2 Reinforcement of column specimens.

(a) Formworks for column specimens of group1

(b) Formworks for column specimens of group2

Figure 3 Special timber formwork.

Figure 4 Casting and vibrating of concrete.

Figure 5 Demolding of column specimens.

and longitudinal bars work together to resist the compression load. (2) Two ties of 8 mm diameter were added at both ends of each column specimen to increase the confinement at column ends. One EMM layer was warped around the ties for each column specimens with combined horizontal reinforcement (phase2 specimens). The EMM layer was secured by connecting it to the ties and longitudinal reinforcement using tying steel wire.

2.2.2. Special timber formwork

Timber formworks with sizes of 15 × 15 × 115 cm and 15 × 15 × 215 cm were designed and manufactured to cast the concrete in vertical position, similar to construction in field. Fig. 3 shows the formworks. Concrete must pass from the core of column specimen through the diamond openings of EMM to form the cover without producing honeycomb and voids. The number of lateral stiffeners provided for the 210 formwork was three times the number of stiffeners needed for the 110 one. The formwork can be easily assembled and separated to parts. Free isolated wooded pieces with size 15 × 15 × 2.5 cm were used to horizontally level the top and bottom edges of the column specimens. Zetolan SH2 (a release agent [25]) was painted on the inner face of the formwork parts. Three sides (U shape) were assembled in horizontal position, the prepared reinforcement cage was carefully placed in the formwork, the fourth side was assembled, stiffeners were added and the formwork was turned in vertical position above horizontal timber base to be ready for casting concrete.

2.2.3. Mixing and casting concrete of RC column specimens

Electric concrete mixer was used to mix the concrete materials with the specific ratios given in Section 2.1. The fresh concrete was transferred by crane to the formwork position and was poured vertically. Concrete was consolidated by electric vibrator to provide good concrete without voids or honeycomb. Fig. 4 shows the casting process. All column specimens were

Figure 6 Curing of column specimens with wet burlap.

demolded (Fig. 5) after 24 h form their time of casting and were enwrapped with wet burlap (Fig. 6) in the laboratory at 25 °C and 55% relative humidity for 28 days. Then the column specimens were uncovered to dry to be ready for testing; Fig. 7.

2.2.4. *Instrumentation and test setup*

Fig. 8 illustrates the instrumentation and test setup. Tests were executed using hydraulic loading machine of 1000 KN capacity. The machine was calibrated before testing to ensure the accuracy of results. The group2 column specimen (210 cm height) was placed on the rigid steel floor of the machine whereas the group1 column specimen (110 cm height) was placed on rigid two RC blocks with total height of 100 cm above the machine floor. Rigid steel plates were fitted under and above the ends of column specimen. Verticality of column specimen was carefully examined and adjusted to ensure perfect centric loading on the column. Steel jackets were clamped and bolted together with high strength bolts to provide enough confinement at loading and supporting ends. Three displacement transducers were mounted on a rigid wooden-stand which was manufactured and fixed into a RC base to be stable enough to monitor the deformation. One transducer was used at top of column specimen in vertical direction to measure the axial deflection whereas the other two were used at mid-height of specimen, in horizontal directions on two perpendicular faces of tested specimen, to measure lateral deflections. The load and displacements were monitored and logged using an automatic data acquisition system.

3. Experimental results and discussion

The results of every pair of column specimens (two identical column specimens) varied within 10%. Therefore, the average results of each pair of tested column specimens were considered in this section. Tables 2 and 3 summarize the ultimate load, the maximum axial deflection, the maximum lateral deflection and energy absorption for group1 and group2, respectively. Fig. 9 shows the load-axial displacement curves for the two groups of the column specimens. Figs. 10–12 visualize the increments in ultimate load, axial deflection and energy absorption, respectively, for phase2 column specimens with respect to phase1 references for both the two groups. Figs. 13 and 14 illustrate the failure modes and crack patterns of tested specimens for the two phases of group1 and group2, respectively. The tabulated and illustrated results (Figs. 9–14 and Tables 2 and 3) are analyzed and discussed in Sections 3.1–3.6.

3.1. *Ultimate load*

Results indicated that one EMM layer, as an additional lateral reinforcement for column specimens with volumetric ties ratio $\rho = 0.2714\%$, increased the ultimate load of the phase2 with 11.02% and 18.55% over phase1 for group1 and group2, respectively. The increment in the ultimate load carrying capacity is more significant for group2 whose slenderness ratio is almost double the ratio of group1.

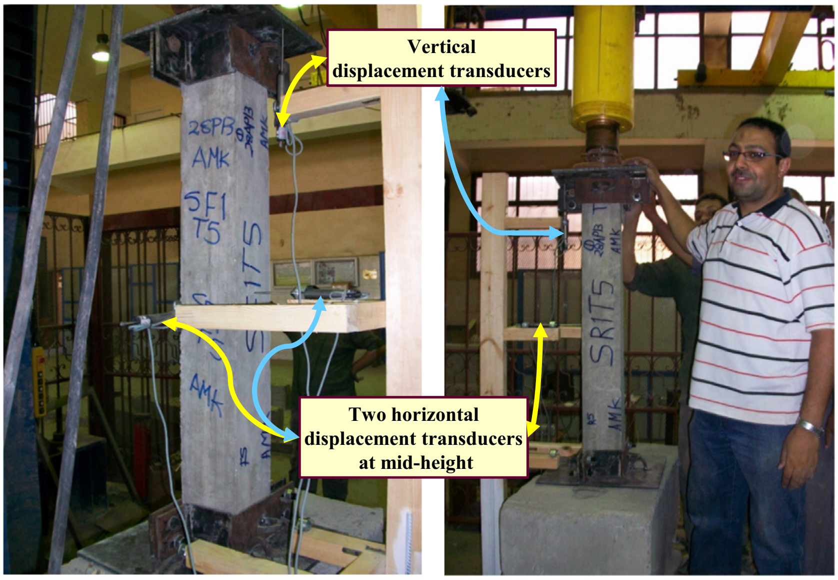
For group1, phase2 column specimens reinforced laterally with an EMM layer and reduced ties volumetric ratio (SF*i*T3 and SF*i*T1) had minor decrease in the ultimate load compared to the control column specimen of phase1. For example, SF*i*T3 column specimen ($\rho = 60\%$ of reference phase1 specimen; SR*i*T5) had ultimate load of 99.04% of referred reference. Also, SF*i*T1 column specimen ($\rho = 20\%$ of SR*i*T5) had ultimate load of 92.92% of phase1. These values indicate that the ties may be completely replaced with single EMM layer for column specimens of group1 ($\lambda = 7.33$) with small loss in the axial load carrying capacity.

For the other group, phase2 column specimens with reduced ties volumetric ratio, LF*i*T6 ($\rho = 60\%$) and LF*i*T3 ($\rho = 30\%$) exhibited little increase in ultimate load over

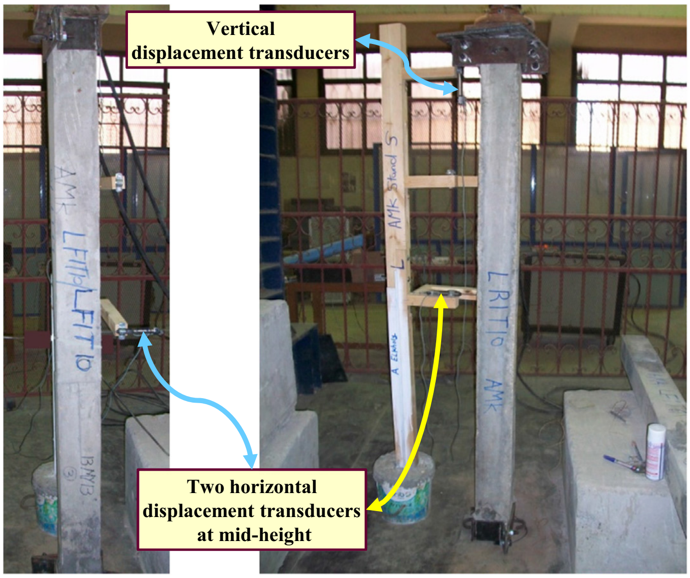
(a) Specimens of group1

(b) Specimens of group2

Figure 7 Column specimens after curing.



(a) Test setup for group1



(b) Test setup for group2

Figure 8 Instrumentation and test setup.

Table 2 Test results for column specimens of group1.

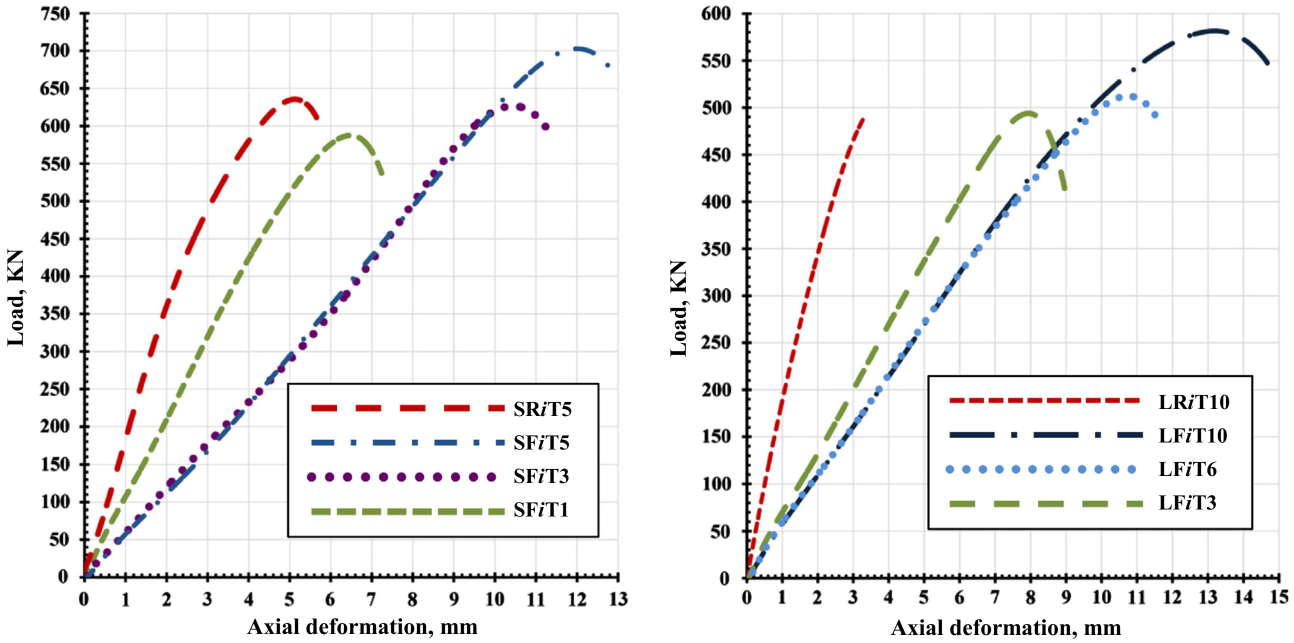
Specimens				Ultimate load		Axial deformation		Lateral deformation		Energy absorption	
Test phase	Specimen ID	Volumetric ratio of ties, ρ (%)	Number of EMM layers	KN	± %	mm	± %	mm	± %	KN.mm	± %
Phase1	SR*i*T5	0.2714	–	636.10	–	5.85	–	1.01	–	2472	–
Phase2	SF*i*T5	0.2714	One layer	706.20	+11.02	12.81	+118.97	1.51	+49.50	4582	+85.36
	SF*i*T3	0.1629		630.01	−0.96	11.30	+93.16	1.37	+35.64	3717	+50.36
	SF*i*T1	0.0543		591.04	−7.08	7.30	+24.79	1.14	+12.87	2612	+5.66

± % Indicates percentage of increment in value relative to that of the phase1.
i = specimen repetition = 1, 2.

Table 3 Test results for column specimens of group2.

Specimens				Ultimate load		Axial deformation		Lateral deformation		Energy absorption	
Test phase	Specimen ID	Volumetric ratio of ties, ρ (%)	Number of EMM layers	KN	±%	Mm	±%	mm	±%	KN.mm	±%
Phase1	LR*i*T10	0.2714	–	492.42	–	3.35	–	4.51	–	943	–
Phase2	LF*i*T10	0.2714	One layer	583.74	+18.55	14.60	+335.82	5.59	+23.95	5194	+450.80
	LF*i*T6	0.1629		516.30	+4.85	11.60	+246.27	5.53	+22.61	3510	+272.22
	LF*i*T3	0.0814		497.28	+0.99	9.05	+170.15	4.92	+9.09	2588	+174.44

±% Indicates percentage of increment in value relative to that of the phase1.
i = specimen repetition = 1, 2.



(a) Column specimens of group1

(b) Column specimens of group2

Figure 9 Average variation of load with respect to axial-deformation.

phase1 column specimens (LR*i*T10). The increments were 4.85% and 0.99%, respectively, for LF*i*T6 and LF*i*T3. In other words, the ties volumetric ratio may be reduced with percentage over 70% with no loss in the ultimate load when single EMM layer is used as additional confining reinforcement for columns with $\lambda = 14$.

It is obvious that the increase in ultimate load and the reduction in ties volumetric ratio are higher for group2 than group1 when single EMM layer is installed as lateral reinforcement. The reasons for higher increment in ultimate load for group2 over group1 are as follows: (1) group2 specimens have higher slenderness ratio which makes the additional confinement provides noticeable increment in ultimate capacity, (2) ρ of group1-phase1 specimens (SR*i*T5) is adequate compared to their λ (therefore, the additional confinement of the EMM layer produced small increment in ultimate load capacity), and (3) ρ of group2-phase1 specimens (LR*i*T10) is small relative to their λ (therefore LR*i*T10 sustained limited ultimate load and influence of confinement was noticeable for phase2). For both groups, higher increments in ultimate load can be achieved by using meshes with better mechanical properties and installing additional EMM layers.

3.2. Axial deflection

At failure, all phase2 column specimens exhibited higher axial deflection than reference phase1 specimens. Therefore, the additional lateral reinforcement of EMM layer resulted in higher axial deformation. The phase2 axial displacement increment for group2 column specimens is much higher than those

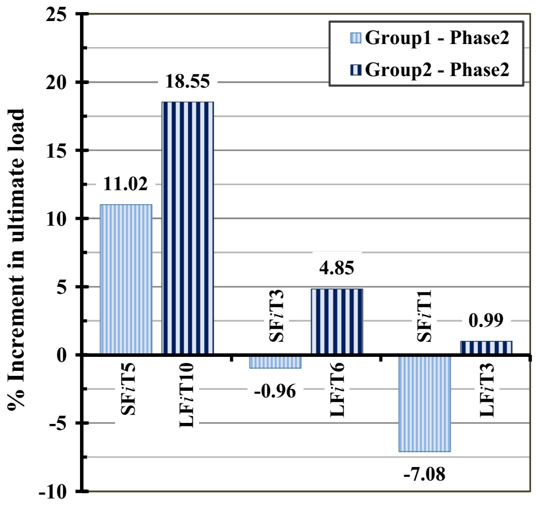


Figure 10 Percent increment in ultimate load of phase2 column specimens.

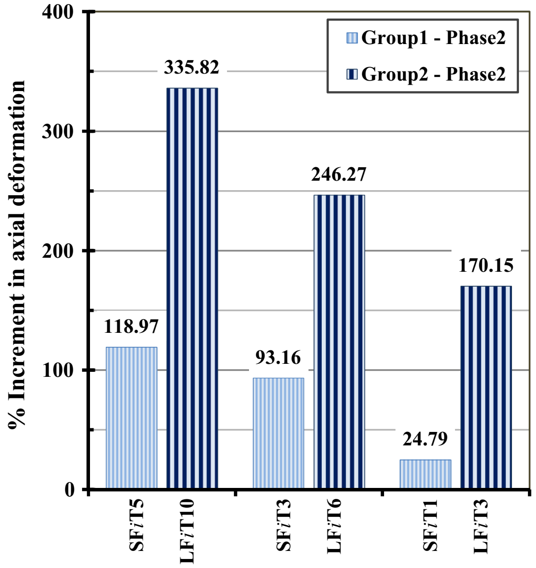


Figure 11 Percent increment in axial deformation of phase2 column specimens.

for group1. In group1, the increments were 118.97%, 93.16% and 24.79% for SF*i*T5, SF*i*T3 and SF*i*T1, respectively, whereas group2 increments were 335.82%, 246.27% and 170.15% for LF*i*T10, LF*i*T6 and LF*i*T3, respectively. The increment was higher (118.97% and 335.82%) for specimens (SF*i*T5 and LF*i*T10) with ρ equal to that of phase1 specimens. Also, it can be noticed that the values of maximum axial shortening for phase2 column specimens in group1 are close to those of group2. Therefore, the source of huge increments ratios in phase2 of group2 is the low axial deformation value (3.35 mm) that the reference column specimen LR*i*T10 exhibits. LR*i*T10 has $\rho = 0.2714\%$ which is small for column with $\lambda = 14$.

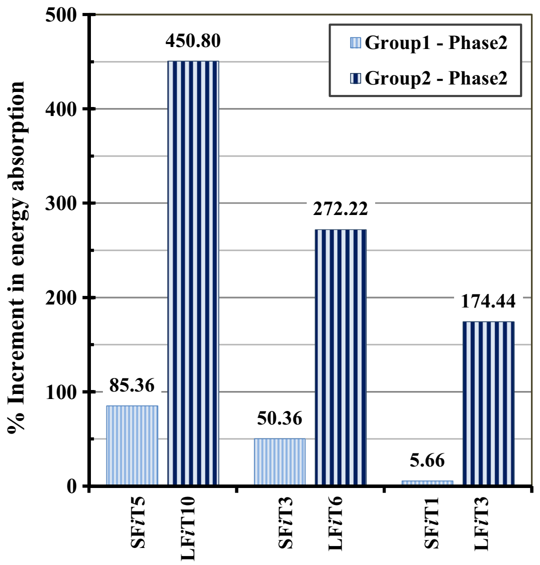


Figure 12 Percent increment in energy absorption of phase2 column specimens.

3.3. Lateral deflection

Lateral deflection is an important issue for long columns. However, all tested specimens represent short RC columns. Tables 2 and 3 indicate that phase2 column specimens experience lateral deflection more than the conjugate phase1 for the two groups. This increment has been achieved with the aid of additional confinement offered by the EMM layer. Higher reduction in ties volumetric ratio results in smaller increment in lateral deflection. Group2 column specimens ($\lambda = 14$) show higher lateral deformation as they exhibit inelastic buckling higher than group1 ($\lambda = 7.33$).

3.4. Ductility

The ductility reveals the ability of a structural member to exhibit large deformation without failure. However, there is no hard rule for absolute definition of ductility [8]. The load displacement curves, given in Fig. 9, show that phase2 column specimens have improved ductility over those of phase1 for the two groups. This improvement is a result of the confining provided by EMM layer. However, this improvement diminishes with higher reduction in ties volumetric ratio as it is noticeable for specimens SF*i*T1 (reduction in $\rho = 80\%$) and LF*i*T3 (Reduction in $\rho = 70\%$).

3.5. Energy absorption

The energy absorption was estimated by calculating the area under load-axial deflection curve for each column specimen. In each group, the increment in energy absorption was highest (85.36%, 450.80%) for phase2 column specimens (SF*i*T5, LF*i*T10) whose ρ are equal to those of corresponding phase1 specimens without reductions. For phase2 column specimens, the EMM layer could relieve the effect of 40%, 80%, 40% and 70% ρ reductions for SF*i*T3, SF*i*T1, LF*i*T6 and LF*i*T3 by absorbing energy 50.36%, 5.66%, 272.22% and 174.44%,

(a) Phase1 **(b)** Phase2

Figure 13 Failure of column specimens of group1.

(a) Phase1 **(b)** Phase2

Figure 14 Failure of column specimens of group2.

respectively, of conjugate phase1 column specimens; SR*i*T5 and LR*i*T10.

The reason for the increased absorbed energy for phase2 column specimen is their flexible behavior originated by high increment values in the axial displacement. Although, the energy absorption values for phase2 columns specimens of group2 are close to those of group1, their increments percentages are higher due to the non-ductile behavior of the reference LR*i*T10 which showed limited axial deformation. It was clarified in Section 3.2 that LRiT10 has limited ρ compared to its λ.

3.6. Cracks

Longitudinal cracks were initiated at approximately 80% of ultimate load for tested column specimens. The failure start was bursting of concrete near column ends where the stress is concentrated due to platen effect of testing machine. The lengths and widths of cracks became evident at approximately 90–95% of ultimate load and eventually concrete cover was spalled off. The failure of phase1 column specimens was sudden and brittle unlike the failure of phase2 column specimens which exhibited significant plastic deformation. Figs. 13 and 14 show that all column specimens failed by crushing of concrete core and buckling of longitudinal reinforcement bars. Moreover, buckling of EMM and breaking of few strands of EMM were observed for phase2 column specimens as shown in Fig. 13. While the crashed part of the concrete core was large and the buckling of vertical bars was excessive for phase1 column specimens, the confining of EMM layer limited the crushing of concrete core and reduced the buckling of vertical bars as shown in Figs. 13 and 14. The buckling of EMM layer, buckling of longitudinal bars and crushing of concrete core were more noticeable for phase2 column specimens of group1 than those of group2 as the latest resist lower ultimate load and exhibit higher overall inelastic buckling. It is expected that increasing the number of layers of EMM or using EMM with better mechanical properties will reduce the buckling of both longitudinal bars and EMM layer and minimize the crushed volume of concrete core.

4. Conclusions

This paper presents investigation for using single EMM layer combined, in practical configuration, with various volumetric ratios of ties as lateral reinforcement for square short RC columns. Based on the results of conducted 16 tests, the following conclusions can be drawn:

1. Adding single layer of EMM as lateral reinforcement to regular volumetric ratio of ties ($\rho_r = 0.2714\%$) increases the ultimate load capacities with 11.02% and 18.55% for square short RC columns with slenderness ratios of $\lambda = 7.33$ and 14 respectively.
2. For column specimens with $\lambda = 7.33$, the EMM layer reduces ρ_r by 40% with minor loss in ultimate load capacity and reduces ρ_r by 60% with only 7.08% reduction in ultimate capacity.
3. For column specimens with $\lambda = 14$, the EMM layer reduces ρ_r by 70% without loss in ultimate load capacity.
4. RC column specimens confined with ties and EMM layer exhibits more plastic deformation and more ductile behavior, compared to specimens confined with only ρ_r ties, provided that their $\rho \geqslant 0.0814\%(\rho \geqslant 30\%\rho_r)$.
5. Warping column specimen with one EMM layer in additional to ρ_r ties increases the energy dissipation with 85.36% and 450.80% for columns with $\lambda = 7.33$ and 14, respectively.
6. A confining EMM layer provides 80% reduction in ties volumetric ratio without shortage in the dissipated energy.
7. Higher ultimate load capacity, better ductile behavior, greater reduction in the ties volumetric ratio and larger dissipation of energy can be achieved by warping additional EMM layers and using EMM with better mechanical properties.
8. Intensive experimental program is required to check the reliability of proposed lateral reinforcement using different types of meshes for short and long RC columns under various loading types and environmental effects.

References

[1] Sheikh SA. Effectiveness of rectangular ties as confinement steel in reinforced concrete columns. PhD dissertation, Department of Civil Engineering, University of Toronto, Canada; 1978.

[2] Mourad SM, Shannag MJ. Repair and strengthening of reinforced concrete square Columns using ferrocement jackets. Cem Concr Compos 2012;34(2):288–94.

[3] Kumar PR, Oshima T, Mikami S. Ferrocement confinement of plain and reinforced concrete. Prog Struct Eng Mater 2004;6(4):241–51.

[4] Saatcioglu M, Grira M. Confinement of reinforced concrete columns with welded reinforcement girds. ACI Struct J 1999;96(1):29–39.

[5] Ksuma B, Tavio, Suprobo P. Axial load behavior of concrete columns with welded wire fabric as transverse reinforcement. Procedia Eng J 2011;14:2039–47.

[6] ACI Committee 549. Guide for the design, construction, and repair of ferrocement; ACI 549.1R-93. Detroit (Michigan, USA): ACI; 1993. Re-approved; 1999.

[7] Ho I, Lam E, Wu B, Wang Y. Monotonic behavior of reinforce concrete columns confined with high-performance ferrocement. J Struct Eng ASCE 2013;139(4):574–83.

[8] Yaqub M, Bailey CG, Nedwell P, Khan QUZ, Javed I. Strength and stiffness of post-heated columns repaired with ferrocement and fiber reinforced polymer jackets. J Compos Part B: Eng 2013;44(1):200–11.

[9] Kaish ABMA, Alam MR, Jamil M, Zain MFM, Wahed MA. Improved ferrocement jacketin for restrengthening of square RC short column. J Constr Build Mater 2012;36:228–37.

[10] Xiong GJ, Wu XY, Li FF, Yan Z. Load carrying capacity and ductility of circular concrete columns confined by ferrocement including steel bars. J Constr Build Mater 2011;25(5):2263–8.

[11] Abdullah, Takiguchi K. An investigation into the behavior and strength of reinforced concrete columns strengthened with ferrocement jackets. Cem Concr Compos 2003;25(2):233–42.

[12] Balaguru P. Use of ferrocement for confinement of concrete. In: Proceedings of the third international conference on ferrocement, Roorkee, India; 1988. p. 296–305.

[13] Singh KK, Kaushik SK. Ferrocement composite columns. In: Proceedings of the third international conference on ferrocement, Roorkee, India; 1988. p. 216–25.

[14] Rao CBK, Rao AK. Stress–Strain curve in axial compression and Poisson's ratio of ferrocement. J Ferrocem 1988;16(2):117–28.

[15] Abdou HAA. Structural behavior of permanent thin ferrocement formwork of columns-filled with various types of concrete. Master thesis. Spupervisors: Shaheen YBI, Tawfik OM. Department of Civil Engineering, Menoufia University, Menoufia, Egypt; 2008.

[16] Shaheen YBI, Hassanen M. Structural behavior of reinforced concrete columns reinforced with various materials. In: Proceedings of 18th international conference on composite materials ICCM18, Jeiu Island, South Korea; 2011. W04-5.

[17] Razvi SR, Saatcioglu M. Confinement of reinforced concrete columns with welded wire fabric. ACI Struct J 1989;86(5):615–23.

[18] EL-Sayad HI, Shaheen AA. Fire resistance of internally or externally confined reinforced concrete columns. Civ Eng Res Mag (CERM) 2005;27(2):459–71.

[19] Egyptian Standards – Building Materials Committee. Cement Part1: Composition, specifications and conformity criteria for common cements; ES 4756-1. Cairo (Egypt): Egyptian Organization for Standards and Quality, EOS; 2009.

[20] British Standards – B/516/6 Cement Specifications Committee. Cement Part1: Composition, specifications and conformity criteria for common cements; BS EN 197-1. London (United Kingdom): British Standards Institution, BSI; 2011.

[21] Egyptian Standards – Building Materials Committee. Aggregates for concrete; ES 1109. Cairo (Egypt): Egyptian Organization for Standards and Quality, EOS; 2008.

[22] Egyptian Standards – Ferrous Products Committee. Steel for the reinforcement of concrete Part1: – Plain bars; ES 262-1. Cairo (Egypt): Egyptian Organization for Standards and Quality, EOS; 2009.

[23] Egyptian Standards – Ferrous Products Committee. Steel for the reinforcement of concrete Part2: – Ribbed bars; ES 262-2. Cairo (Egypt): Egyptian Organization for Standards and Quality, EOS; 2009.

[24] Egyptian Code Committee. Egyptian code for design and construction of concrete structures; ECP 203-2007. Cairo (Egypt): Housing and Building National Research Center, HBRC; 2010

[25] Chemicals for Modern Buildings CMB. Technical data sheet of release agent; ZETOLAN SH2. Cairo (Egypt): CMB; 2013

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