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Repair and strengthening of reinforced concrete square columns using ferrocement jackets

S.M. Mourad, M.J. Shannag *

Department of Civil Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia

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ABSTRACT

A series of 10 one-third scale square reinforced concrete column specimens were cast; preloaded under axial compression up to various fractions (0%, 60%, 80%, and 100%) of its ultimate load; repaired using ferrocement jackets containing two layers of Welded Wire Mesh (WWM) encapsulated in high strength mortar; and then retested to failure. The overall response of the specimens was investigated in terms of load carrying capacity, axial displacement, axial stress and strain, lateral displacement, and ductility. The test results indicated that jacketing reinforced concrete square columns with this form of ferrocement provided about 33% and 26% increases in axial load capacity and axial stiffness, respectively, compared to the control columns. The test results also indicated that repairing similar reinforced concrete columns (after preloading them to failure) with the same ferrocement jacket almost restored their original load capacity and stiffness. Furthermore, the repaired columns failed in a ductile manner compared to the brittle failure exhibited by the control columns.

1. Introduction

Repair and rehabilitation of existing structures is becoming a major part of construction activities. Some estimates have indicated that, worldwide, in 2010 the expenditure for maintenance and repair work will represent about 85% of the total expenditure in the construction field. Furthermore, it has been forecast that US$50 billion will be spent just for the restoration of deteriorated bridges and viaducts in the US [1]. Most of the rehabilitation works consist of repairing old deteriorating structures, and structures damaged by earthquakes and natural disasters. Hence the development of cost-effective and long-lasting repair/retrofit methods can greatly reduce maintenance requirements, increase life safety and increase the service life of concrete structures.

Typical damage in reinforced concrete columns has been attributed to the lack of confinement resulting from large spacing of ties in the columns, and the use of 90° hooks, even in conjunction with close tie spacing. However, researches conducted in the past have shown that the compressive strength of concrete core, ultimate compressive strain of concrete and ductility of the column can be increased significantly by providing a suitable means of external confinement [2–4]. Welded Wire Mesh (WWM) appears to provide such confinement when it is used with a thin-wall layer of mortar. Due to its thin-walled construction, such ferrocement is ideally suited for structures in which predominant membrane stresses occur. Ferrocement has been successfully used in new structures, repair and rehabilitation of existing structures and marine environment. There has been increasing activity with ferrocement construction throughout the world including many countries such as USA, Canada, Australia, China, India, Thailand, Mexico, and Indonesia and in marine environments [5,6]. Wide availability of materials, low cost, and lack of need for skilled labor make ferrocement suitable for both prefabrication and self-help construction in developing regions, and an attractive alternative technique for strengthening and rehabilitation of concrete structures.

Many researchers have emphasized the potential uses of ferrocement laminates in repair and rehabilitation of concrete structures. Rosenthal [7], and Winokur and Rosenthal [8], have demonstrated an innovative use of ferrocement as columns after conducting a preliminary test program. Razvi and Saatcioglu [9], investigated the behavior of small scale reinforced concrete columns specimens when Welded Wire Fabric was used as lateral reinforcement to confine the concrete core of the column. Various combinations of WWF and tie reinforcement have been used as confinement steel. It was shown from the experimental results that, the use of WWF as confinement reinforcement improves concrete strength and ductility very significantly.

Ferrocement encased short circular and square concrete columns with unreinforced and reinforced cores were investigated by Kaushik et al. [10], it was observed that the ferrocement encasement increases the strength and ductility of columns for both axial and eccentric loading conditions. Another interesting research work was done by Ahmad et al. [11], to investigate the possibility of using

* Corresponding author. Tel.: +966 1 467 6928; fax: +966 1 467 7008.
E-mail address: mjshanag@ksu.edu.sa (M.J. Shannag).

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ferrocement as a retrofit material for masonry columns, the study demonstrated that the use of ferrocement coating strengthens brick columns significantly and improves their cracking resistance.

A preliminary investigation into repair of short square columns using ferrocement was conducted by Nedwell et al. [12], it was found that the use of ferrocement retrofit coating increased the apparent stiffness of the columns and significantly improves the ultimate load carrying capacity. A proposed method presented by Fahmy et al. [13], for repairing reinforced concrete columns using ferrocement laminates as a viable economic alternative to the highly expensive conventional jacketing methods, the experimental results demonstrated that irrespective of the pre-loading level or the mesh type, better behavior and load carrying capacity for all test specimens could be achieved compared to their original behavior.

Recently, a study by Mansure et al. [14], on strength of bolted moment connections in ferrocement construction indicated that the mode of failure of a joint depends on whether the applied moment is in the opening or closing mode. Under the closing mode, failure always occurs by shear punching of the bearing plates through the connected ribs. In contrast, failure in the opening mode occurs by bending failure of either the connected or the longitudinal rib. Also, some other studies [15,16] indicated that distributed fibers and textiles are alternative reinforcements in thin repair layers. Martinola et al. [15] showed that strengthening and repair of RC beams with fiber reinforced concrete is an effective technique both at ultimate and serviceability limit states. Mechtcherine, and Lieboldt [16] conducted experimental and analytical investigation on the permeation of water and gases through cracked textile reinforced concrete (TRC). They showed that the permeation of oxygen and water through cracked TRC correlated with the induced strain and the crack characteristics, i.e. the number of cracks and crack width.

As demonstrated above, using ferrocement laminates in repairing and strengthening structural elements has been proven to be efficient in providing additional strength and ductility. In addition such technique has a major advantage among others, that it is being considered as a low cost repair technique. However, in some situations, WWMs that conform to ACI standards may not be available in the market, consequently, that can result in using other WWMs that are intended to be used in non-structural purposes. Those types of meshes are made from galvanized steel, used in fencing and other purposes, are commercially available in hardware shops with low prices. Utilizing such ordinary WWM in ferrocement jacket structural applications need more investigation.

The main objectives of this research are to investigate the effectiveness of applying high strength ferrocement jackets containing ordinary locally available Welded Wire Meshes (WWM) on one-third-scale reinforced concrete square columns; and to study the behavior of damaged and preloaded columns after repairing them with these jackets, in terms of strength gain, ductility and failure modes.

2. Experimental program

The experimental program consists of testing one-third scale square (150 × 150 mm) column specimens with a height of 1000 mm in three phases as follows; *Phase 1:* Control column specimens without any preloading and without ferrocement jackets, *Phase 2:* Jacketed column specimens without any preloading but with ferrocement jackets, and *Phase* 3: Strengthened preloaded column specimens include columns strengthened with ferrocement jackets after preloading them with 60%, 80% and 100% of their ultimate axial strength.

The number and details of the square reinforced concrete column specimens are given in Table 1. The details of reinforcements and dimensions of the square reinforced concrete column specimens are shown in Fig. 1. The ferrocement jacket used in the experimental program was the same for all column specimens and consisted of two layers of WWM wrapped around the column and encapsulated in high strength mortar. The two layers of WWM were chosen for all specimens because it was found to be reasonably managed and handled during wrapping according to the available facilities in the lab.

2.1. Materials properties

The materials used in preparing the concrete mix include ordinary Portland cement (ASTM Type I), crushed limestone coarse aggregate with a maximum size of 10 mm, an absorption capacity of 1.5%, and an oven dry bulk specific gravity of 2.60, a mixture of washed sand and natural silica sand with an absorption capacity of 1.5% and 0.1% and an oven dry bulk specific gravity of 2.56 and 2.52 respectively, and tap water. The concrete mix used consists of 300 kg/m^3 Portland cement, 700 kg/m^3 crushed limestone, 600 kg/m^3 washed sand, 450 kg/m^3 silica sand, and 195 kg/m^3 free water. The concrete mix was designed in order to obtain a target cylindrical compressive strength of 25 MPa after 28 days. It was intended to use and investigate the effectiveness of using ordinary locally available WWM as a low cost material in rehabilitation and upgrading reinforced concrete columns. The WWM used in the jackets had square openings of (12 × 12 mm) and wire diameter of 0.94 mm. Tensile tests were performed on three coupons and the wire yield strength was determined in accordance to ACI committee 549, 1988 [17]. The average yield strength was 385 MPa at a yield strain of 0.0037, and the average ultimate tensile strength was 524 MPa, while the average modulus of elasticity was 106 MPa.

Different mixes of mortar were designed and prepared in order to develop high strength and flowable mortar [18]. The materials used in preparing mortar specimens include locally available ordinary Portland cement (ASTM Type I) with a specific gravity of 3.15, natural silica sand with a specific gravity of 2.60 and a fineness modulus of 1.65, silica fume and fly ash were in powder form with a specific gravity of 2.2 and 2.3 respectively. Superplasticizer of a melamine formaldehyde sulfonated superplasticizer type with a specific gravity of 1.21 was incorporated in all mixes to maintain the same degree of workability. The mortar mix proportions were 1:2:0.15:0.05:0.4:0.04 by weight of type I cement, silica sand, silica fume, fly ash, water and superplasticizer, respectively. The mortar mix achieved a compressive strength of 63 MPa and tensile strength of 5 MPa after 28 days and a flow of 132%.

2.2. Preparation of specimens

2.2.1. Preparation of column specimens

The longitudinal reinforcement and stirrups were previously prepared before placing it in horizontal wooden molds that were specially made for the square column specimens. One strain gage was attached at the middle of each of the two diagonally longitudinal reinforcement bars of each column. The readings of those strain gages were used at the initial stage of the test to adjust the specimen in the testing machine to ensure perfect verticality with minimal eccentricity during testing by obtaining equal readings in those strain gages. In addition, two strain gages were attached to the middle stirrup of the column to determine the lateral strains in the stirrups and to compare its readings with those pasted on the concrete surface. The prepared steel cage was carefully placed in the wooden mold after oiling its surface so that it was spaced from the sides of the molds by 13 mm using wooden spacers at edges, which is considered to be the concrete cover. The molds with the steel cages were placed on the vibration table at a low speed while the concrete was poured. After casting,

Table 1
Details of tested column specimens.

No. of specimens	Designation	Preload (fraction of ultimate load) (%)	Ferrocement jacket
2 (control)	SC-1 SC-2	0	None
2	SJ-0-1 SJ-0-2	0	Two layers of welded wire mesh encapsulated in high strength mortar
2	SJ-60-1 SJ-60-2	60 60	
2	SJ-80-1 SJ-80-2	80 80	
2	SJ-100-1 SJ-100-2	100	

SC: control specimens; SJ-XX: jacketed specimens after preloading by XX% of ultimate load.

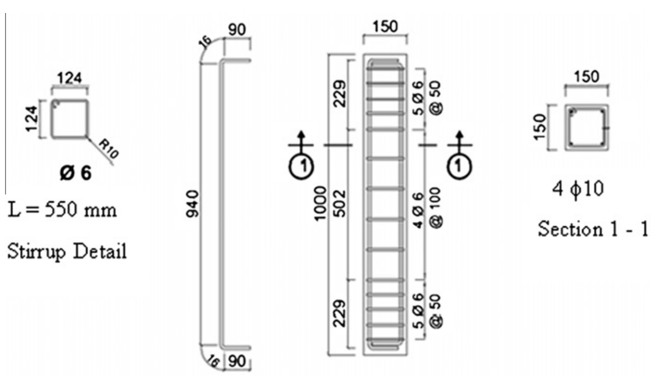


Fig. 1. Reinforcement details and dimensions of square column specimen.

the specimens were covered with wet burlap in the laboratory at 23 °C and 65% relative humidity. The specimens were demolded after 2 days and wrapped with damp cloth for 14 days. The control and preloaded column specimens were prepared for testing after 28 days from casting. While other column specimens were tested after applying the ferrocement jackets.

2.2.2. Preparation of ferrocement jackets

The ferrocement jackets were prepared using two layers of Welded Wire Meshes (WWM) and covered with a flowable high strength mortar jacket using specially designed molds. The ferrocement jackets were applied to the unloaded column specimens after 28 days from the day of casting. While the ferrocement jackets were applied to the preloaded and failed columns after being tested to 60%, 80% and 100% of their axial capacity. Before applying the ferrocement jackets all column specimens were sand-blasted to roughen their surfaces for a better bond between the concrete surface and the applied mortar layer. Two horizontal strain gages were placed at the

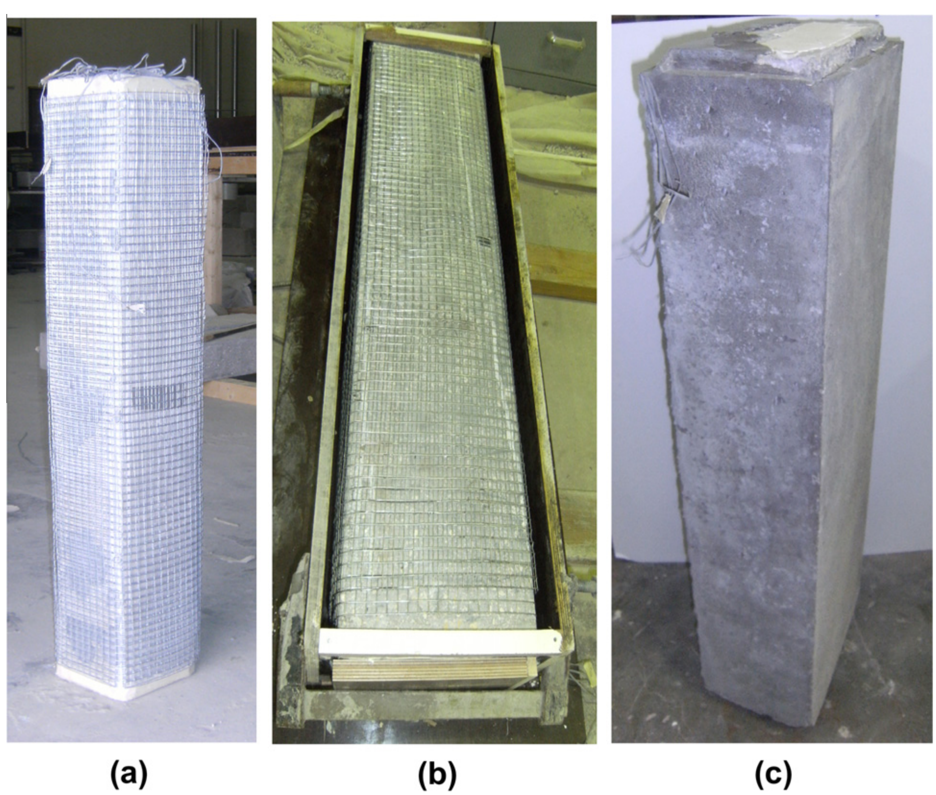
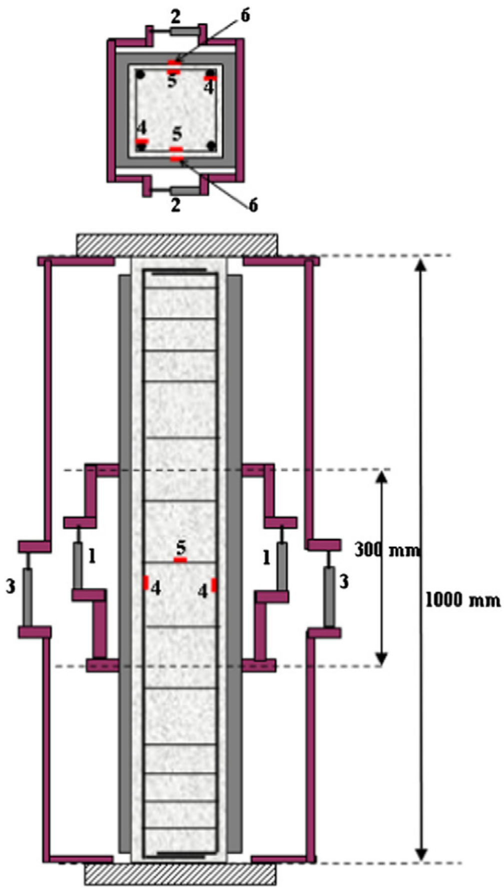


Fig. 2. Stages of preparing ferrocement jackets.



(1) Two vertical LVDTs at gage distance 300mm
(2) Two horizontal LVDTs across the column section
(3) Two vertical LVDTs at gage distance 1000 mm
(4) Two strain gages on longitudinal reinforcement
(5) Two strain gages on middle stirrups
(6) Two horizontal strain gages on concrete surface

Fig. 3. Different instrumentation used for column test.

two opposite sides of the concrete column at its mid height, in order to determine the lateral strains at the concrete surface. The process of wrapping the WWM around the specimen includes attaching the edge of the mesh to the surface of the specimen using a high adhesive bonding paste known as Sikadur-31, and then wrapping the two layers of WWM around the column specimen. The joints of the mesh were secured at different locations together using double thin steel wires that are commonly used in tying reinforcing bars. To maintain the integrity of the WWM layers and to increase its attachment to the plain concrete specimens, the bonding paste of Sikadur-31 was applied at four spots along the height and clamped to the specimen until it hardened. Fig. 2a shows the final form of the specimen after wrapping the WWM. It can be noticed that the ends of the WWM layers were 20 mm away from the ends of the concrete columns, since it was decided that the ferrocement jackets do not reach the ends of the specimens so that it only provides confinement without applying any vertical compression loads on the ferrocement jackets. The wrapped concrete column was placed in specially prepared oiled wooden molds that allow for casting 20 mm ferrocement jackets. Wooden spacers of 20 mm thick and 20 mm wide were placed around the specimens at its ends to secure its position inside the molds. Such position allows for 20 mm thickness of mortar to surround the specimen except at its ends, as shown in Fig. 2b. The mortar mix was poured around the column specimens, and the sides of the wooden molds were vibrated to ensure the full penetration of mortar around the WWM. The specimen's top surface was finished and covered with damped cloth for two days, and covered with damped cloth for another 14 days after removing the molds. The jacketed column specimens were kept uncovered to dry in the laboratory environment until testing. Fig. 2c shows the final form of the column specimens after applying the ferrocement jacket.

2.3. Instrumentation and test setup

Several instrumentations were used not only to measure the axial and transverse displacements and strains but also to verify those measurements. Special steel-frame setup was used to mount the LVDTs away from the surface of the specimen. The strain gauges were pasted on the surface of concrete, reinforcing bars and stirrups. A schematic sketch showing the positions of the LVDTs and strain gauges on the specimen is presented in Fig. 3 and demonstrated using photos in Fig. 4.

The column specimen was placed on the floor of the AMSLER compression machine with a capacity of 10,000 kN as shown in Fig. 4. Careful attention was paid to ensure the verticality of the column during the test to obtain perfect centric loading on the column. Both bottom and top ends of the column were leveled horizontally using thin layer of gypsum before placing the rigid steel plates at the ends of the column. Steel jackets were clamped and bolted together to increase the confinement and to prevent premature failure at column ends. All instrumentations were connected to the data acquisition system. The test was carried out under displacement control at a rate of 0.5 mm per minute, and the readings of all instrumentations were taken approximately at each 5 s until the end of the test.

3. Discussion of test results

Each column specimen, its collected measured data was analyzed in order to obtain the axial stresses in concrete and reinforcements, axial and lateral deformations, as well as axial and lateral strains. Axial stresses in concrete were obtained after subtracting the axial loads taken by the longitudinal reinforcement. The axial and lateral strains of the column were obtained from the measured axial and lateral displacements that were obtained from the average readings of the LVDTs. Similar behavior was observed in similar specimens, therefore only the results of one specimen are demonstrated in the graphs for clarifying purposes.

3.1. Load–displacement and stress–strain relationships

The axial load–axial and lateral displacements relationships as well as the axial concrete stress–axial and lateral strains relationships were obtained for each tested specimen. Fig. 5 shows the axial load–axial and lateral displacements relationships for one specimen of control columns (SC-2), jacketed columns (SJ-0-2) and strengthened preloaded columns (SJ-60-1 and SJ-80-1) as well as the strengthened failed column (SJ-100-1). Fig. 6 shows the axial concrete stress-axial and lateral strains relationships for the same specimens. It can be observed that the jacketed specimen (SJ-0-2) reported significant increase in both load carrying capacity and axial stiffness as compared to the control specimen (SC-2); such increases are about 33% and 26% respectively. It can be noticed that the strengthened preloaded column specimens SJ-60-1 and SJ-80-1 recorded higher load capacity and axial stiffness as compared to the control SC-2, but lower than those from the jacketed column specimen SJ-0-2. Strengthening the failed column SJ-100-

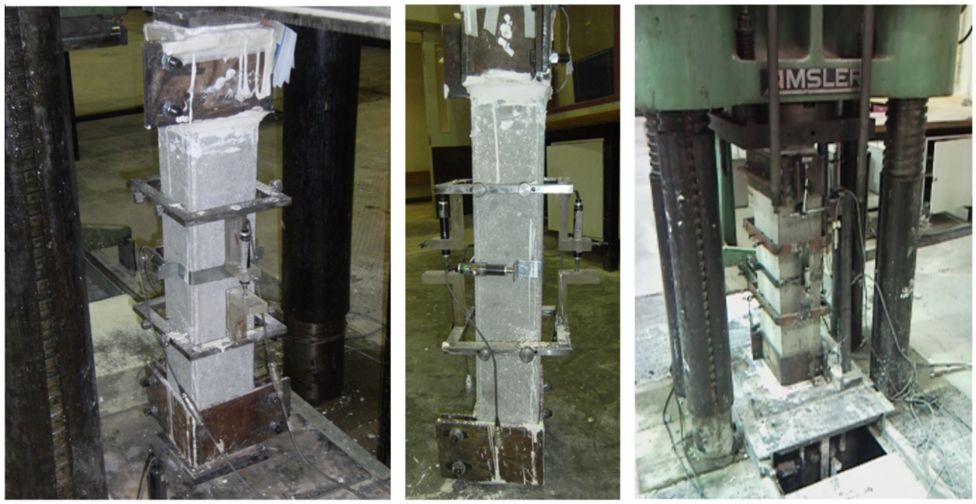


Fig. 4. Instrumentation and test setup.

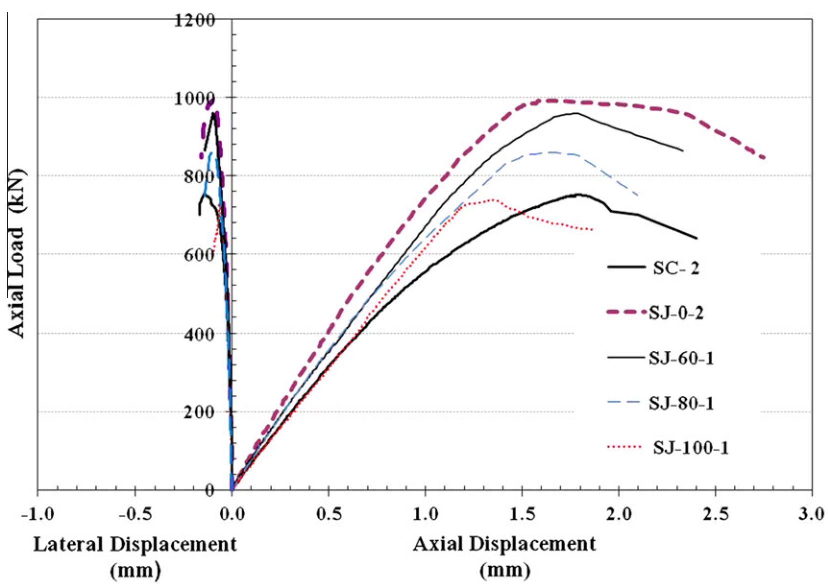


Fig. 5. Load–displacement relationships for tested specimens.

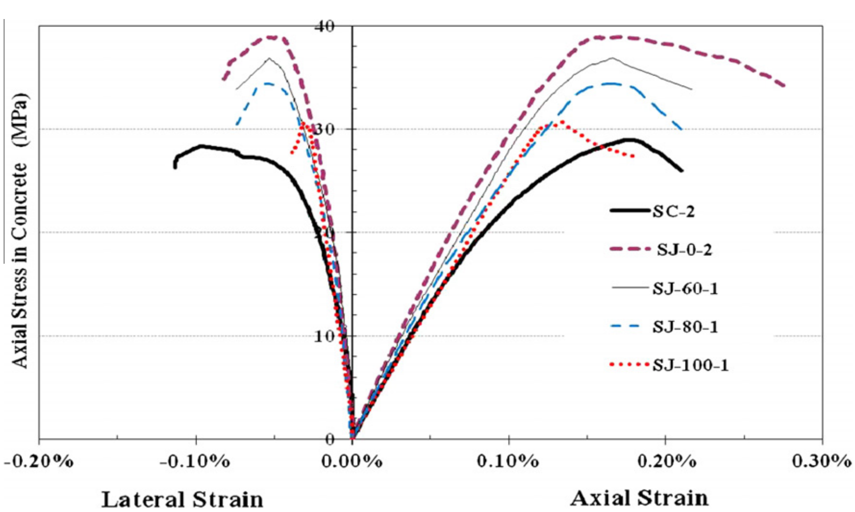


Fig. 6. Stress–strain relationships for tested specimens.

Table 2
Test results of control, jacketed and preloaded jacketed columns.

Specimen designation	Ultimate load		Ultimate axial stress in concrete		Initial axial stiffness	
	(kN)	%[a]	(MPa)	%[a]	(MPa)	%[a]
SC-2	750	–	29	–	26,870	–
SJ-0-2	994	133	39	135	33,760	126
SJ-60-1	960	128	37	128	28,816	107
SJ-80-1	860	115	35	121	26,880	100.4
SJ-100-1	740	98.7	31	107	25,840	96.2

[a] Value relative to that of the control columns.

1 restored almost its original capacity with approximately the same axial stiffness and with less ductility. No significant change was observed in the maximum axial and lateral strains of the strengthened preloaded column specimens as compared to those of the control column specimen. However, the strengthened failed columns recorded less axial and lateral stains as compared to those of the control columns due to the existence of minor cracks in the original concrete column. Results of tested specimens are summarized in Table 2.

3.2. Load carrying capacity

Results indicated that repairing tied reinforced concrete columns that were preloaded up to 60% and 80% of their ultimate load carrying capacity, caused 28% and 15% increase in load carrying capacity. Insignificant increase in axial stiffness was observed for preloaded specimens. The test results have also shown that repairing severely damaged (failed) columns using the same ferrocement jacket restored almost the original load carrying capacity and stiffness of control columns prior to failure, with a significant loss in ductility that can be overcome by using meshes with better mechanical properties matching those present in the ACI guidelines on ferrocement [17]. Furthermore, it is interesting to observe, that the load–displacement response of repaired preloaded and repaired failed columns, outperformed and almost matched the response of control columns, respectively.

3.3. Cracking patterns and failure modes

3.3.1. Unloaded columns (control and jacketed)

The control column specimens (Phase 1) and the jacketed column specimens (Phase 2) were tested until they reached their maximum load. The failure was initiated by vertical hairline cracks at the middle part of the control specimen and in the mortar of ferrocement jackets at the middle portion of the jacketed column specimens. The vertical cracks became visible at about 90% to 95% of the ultimate load. The number and width of these cracks started increasing with the increase in axial load until the specimen reached its failure load. The control specimens exhibited sudden brittle failure mode whereas the jacketed specimens exhibited a gradual ductile failure mode. The failure in jacketed specimens was mainly caused by the failure of WWM at the corners of the specimen that resulted in the separation and bulging of the mortar layer from the specimen. Fig. 7 shows the typical failure mode of the jacketed column specimens. The jacketed column specimens showed significant increase in both axial load capacity and axial stiffness as compared to the control specimens. It is worth mentioning that such increases were almost due to the confinement offered by the ferrocement jackets, since the jackets were not reaching the end of specimens. Insignificant variations in axial displacements, lateral displacements and resulted strains were reported. Since only two layers of WWM were used in the ferrocement jackets, such insignificant variation is expected due to the early failure of WWM.

3.3.2. Preloaded columns (repaired)

The failure of repaired preloaded columns occurred gradually by mortar cracking and bulging near the middle part of the column and failure of the WWM near the corners, as shown in Fig. 8. However, in case of strengthened failed columns, progressive failure mode was observed as a result of the pre damage caused by preloading the columns to their full capacity.

4. Conclusions

Based on the test results of this investigation the following conclusions can be drawn:

1. Ferrocement jackets have been utilized as an alternative repair/strengthening technique for increasing the axial load carrying capacity and ductility of tied reinforced concrete columns. The investigation was limited to ferrocement

Fig. 7. Typical failure mode for jacketed column specimens without preloading.

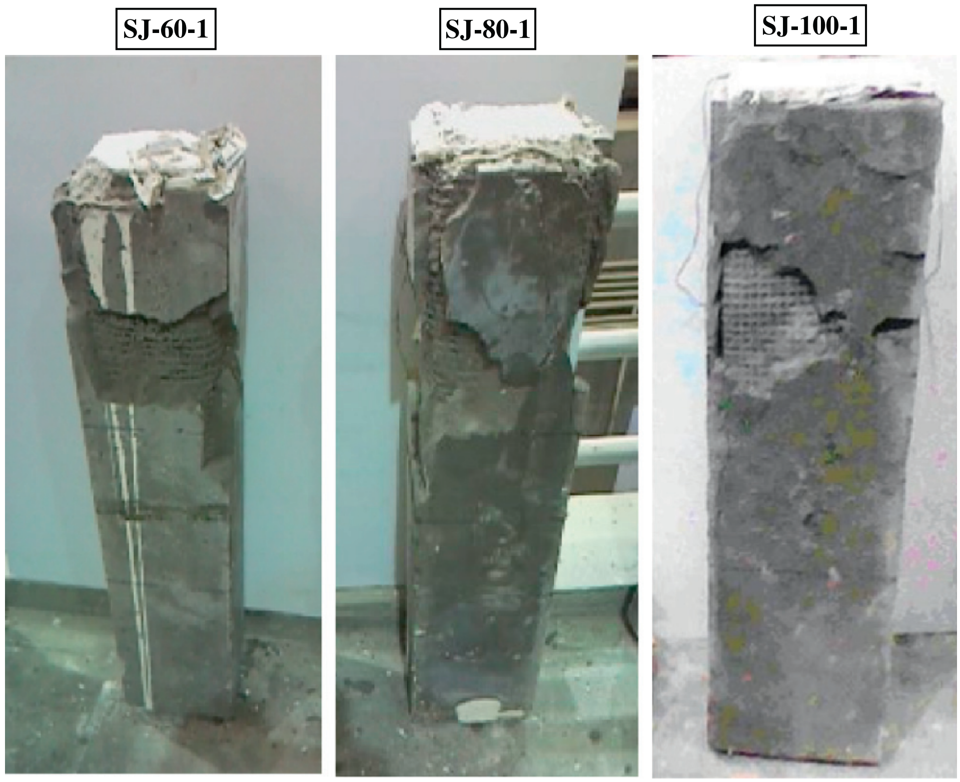


Fig. 8. Typical failure modes for column specimens jacketed after preloading.

jackets containing two layers of ordinary Welded Wire Meshes (WWM) encapsulated with 20 mm high strength ferrocement mortar. The limitation in number of layers was due to matters related to managing and handling the WWM during wrapping the specimens.

2. Test results indicated that strengthening unloaded reinforced concrete columns of 150 × 150 mm square cross section and a height of 1000 mm, with two layers of WWM ferrocement jackets showed about 33% and 26% increase in axial load carrying capacity and stiffness respectively, compared to control columns.
3. Test results indicated that repairing similar reinforced concrete columns of square cross section preloaded up to 60% and 80% of their ultimate load carrying capacity, with the same jackets showed about 28% and 15% increase in axial load carrying capacity as compared to control columns.
4. Test results indicated that repairing similar reinforced concrete columns of square cross section preloaded up to failure with the same jacket restored almost the original load carrying capacity and stiffness of control columns.
5. The strengthened and repaired columns failed in a ductile manner characterized by the larger area enclosed by the load displacement curve at the end of the test compared to a brittle failure in case of control columns. However, the repaired failed columns showed a significant loss in ductility due to the existence of cracks in failed columns.

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