ARTICLE

JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)

مــــجلــة جـــــامعة بـــــــابـل للعلــــــوم الهندسية

Vol. 32, No. 4. \ 2024 ISSN: 2616 - 9916

Experimental and Analytical Investigations on Biaxially Loaded Reinforced Concrete Columns Retrofitted by Ferrocement Jacketing

Hesham Salim Al-Rawe[1]* Sofyan Younis Ahmed[2] Salwa Mubarak Abdullah[3]

[1]*Department of Civil Engineering, University of Mosul, Mosul, Iraq.*

***Corresponding author** hesham.salim@ntu.edu.iq

[2]*Department of Civil Engineering, University of Mosul, Mosul, Iraq.*

sofyan1975@uomosul.edu.iq

[3]*Department of Civil Engineering, University of Mosul, Mosul, Iraq.*

salwa_hano@uomosul.edu.iq

Received:	29/4/2024	Accepted:	16/7/2024	Published:	14/8/2024

Abstract

Biaxially loaded reinforced concrete columns are structural components impacted by axial compression and bending forces in two directions. This study involves retrofitting of preloaded columns using ferrocement jacketing consists of high performance mortar and reinforced with geogrid mesh. Six reinforced concrete short columns (150*150*1700) mm are cast with concrete bracket at each end. Two of them served as control columns which are loaded till failure, while the other four columns are preloaded and then retrofitted. They are preloaded up to (65 & 85) % of the total failure loads of control specimens. The eccentricity value of loading changed between (30) mm and (70) mm for the both axes. The results proved that using this technique of retrofitting increases the ultimate carrying capacity of the preloaded columns up to (38.8) % comparing to the control specimens. It also improves their crack resistance and failure behavior. Finally, the experimental results are compared with the analytical results obtained from finite element analysis (FEA) using ABAQUS program.

Keywords: Reinforced concrete columns, Ferrocement jacketing, Geogrid mesh, Finite element analysis, Ultimate capacity.

1. Introduction

Reinforced concrete (RC) columns are construction elements usually efficient in moving vertical forces of buildings to the ground. These elements made of concrete with steel reinforcement to develop their durability and load carrying capability. Repairing of the RC columns is necessary to guarantee their efficacy for a long time. Therefore, regular inspect is quite significant to assign and adjust any issue in the structure.

Retrofitting process aims to improve performance of the deteriorated components through using of various techniques such as fiber polymers, steel plate and external jacketing [1].

Ferrocement is one of the most famous external jacketing methods based on its inexpensive and accessible raw materials, low impact on the environment, waterproofing features with high quality performance and strength [2, 3, 4, 5].

Kaish et al. [6] investigated performance of eight square RC columns which are eccentrically loaded and jacketed with ferrocement. The columns are with (100*100*600) mm dimensions which are divided into two control un-jacketed and six jacketed specimens. All the specimens are tested till failure with (25) mm of loading eccentricity. The findings of this study referred that both load carrying capacity and ductility of the ferrocement jacketed columns are enhanced comparing to the control specimens. Akram S. et al. [7] studied eight circular RC columns subjected to eccentric and concentric loads with dimensions of (1000) mm in length, (100) mm for the internal diameter and (220) mm for the external diameter. The columns are jacketed with ferrocement and tested with respect to their number of mesh layers, value of loading eccentricity and load distribution. The results proved an important development in load carrying capacity of the jacketed columns comparing to the control specimens. Using two layers of welded steel mesh enhanced the capacity up to 67% for the concentric loaded columns and up to 78% for the eccentric ones. While columns failed due to either concrete crushing or yielding of steel reinforcement bars.

Mahmoud Elsayed et al. [8] investigated the behavior of columns jacketed with ferrocement and subjected to biaxial loading approach. They adopted finite element using ANSYS software to analyze 25 model of RC columns. Factors taken into account were thickness of ferrocement, number of layers of expanded wire mesh and strength of the used mortar. The numerical outcomes showed that ferrocement jacketing was effective in strengthening the biaxially loaded columns. The ultimate loads and stiffness of every wrapped specimen were higher than those of the unwrapped columns. Fayzul Bari A. et al. [9] looked at how well RC columns damaged by fire may be repaired using ferrocement confinement. By contrasting the behavior of retrofitted, controlled and fire-damaged specimens, the effectiveness of confinement is determined. Six rectangular short columns with dimensions of (150*150) mm and height of (800) mm have been tested for this purpose. Four specimens are damaged in a wooden fire and two of them are then retrofitted using ferrocement with one and two layers of wire mesh reinforcement. As a result of the fire damage, the columns' load capacity has dropped by roughly 46%. However, using ferrocement confinement improved the capacity of damaged columns by 23% and 49% for one and two layers of wire mesh reinforcement respectively.

The current research aims to investigate the ability of using ferrocement jacketing in retrofitting of biaxially loaded reinforced concrete short columns. The main gap of the study involves using of geogrid mesh reinforcement with high performance mortar instead of the traditional ferrocement which consists of steel wire mesh with normal cement-sand mortar.

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلــة جـــامعة بــــابــل للعلـــــوم الهندسية
Vol. 32, No. 4. \ 2024 ISSN: 2616 - 9916

2. Material Properties

2.1 Cement

All the specimens are made using ordinary Portland cement (Type 1) which satisfies the requirements of IQS: 5/2010 [10]. Table (1) illustrates physical properties of used cement.

Table (1) Physical Properties of Cement.

No.	Characteristics	Value	Specifications (IQS: 5/2010)
1	Standard consistency	0.30	…..
2	Fineness (sieve no.170) %	5	≤ 10 (IS: 12269)
3	Compressive strength (3 days) MPa	21.4	≥ 15
4	Compressive strength (7 days) MPa	29.1	≥ 23
5	Initial setting time (min)	98	≥ 45
6	Final setting time (min)	204	≤ 600

2.2 Fine Aggregate

Locally available sand passing sieve No. 4 has been used as fine aggregate for concrete mix of columns. Its grading satisfies to the IQS: 45/2010 [11] as stated in Table (2).

Table (2) Sieve Analysis of Fine Aggregate.

Sieve Size (mm)	Retained Cumulative (%)	Passing (%)	Specifications (IQS: 45/2010)
4.75	9	91	90-100
2.36	23.5	76.5	75-100
1.18	35.1	64.9	55-90
0.6	47.5	52.5	35-59
0.3	71.1	28.9	8-30
0.15	90.4	9.6	0-10

2.3 Coarse Aggregate

Locally available gravel with 14 mm maximum aggregate size has been used as coarse aggregate in preparation of the specimens. Its grading satisfies to the IQS: 45/2010 [11] as stated in Table (3).

Table (3) Sieve Analysis of Coarse Aggregate.

Sieve Size (mm)	Retained Cumulative (%)	Passing (%)	Specifications (IQS: 45/2010)
20	0	100	100
14	10	90	90-100
10	47	53	50-85
5	97.5	2.5	0-10

ARTICLE

JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)

مـــجلــة جـــامعة بـــــابـل للعلـــــوم الهندسية

Vol. 32, No. 4. \ 2024 ISSN: 2616 - 9916

2.4 Reinforcement Steel

Table (4) shows the properties of reinforcement steel bars used in this study. They satisfy with specifications of ASTM A615/A615M-01b Grade 60 (420 MPa) [12].

Table (4) Properties of Reinforcement Steel.

Bar Diameter (mm)	Yield Stress (MPa)	Ultimate Strength (MPa)	Elongation (%)
10	510	618	14.7
12	488	669	16.8
16	521	689	18.1

2.5 Mix Design

In order to produce specimens with the required compressive strength of (27) MPa at (28) days, as specified by the British standard BS 1881: Parts 116 [13], the proportions of concrete mixing were designed through a series of experimental mixes. The weight-ratio of cement, sand and gravel was (1: 1.5: 2.5), with a water/cement ratio of (0.5) utilized to prepare the concrete for this investigation.

2.6 Geogrid Mesh

Biaxial geogrid mesh made from polymer with opening dimensions (21*21) mm was used in reinforcement of ferrocement. Its ultimate tensile strength equals to 1100 MPa as experimentally tested. Figure (1) shows the used geogrid mesh with its testing process inside the lap.

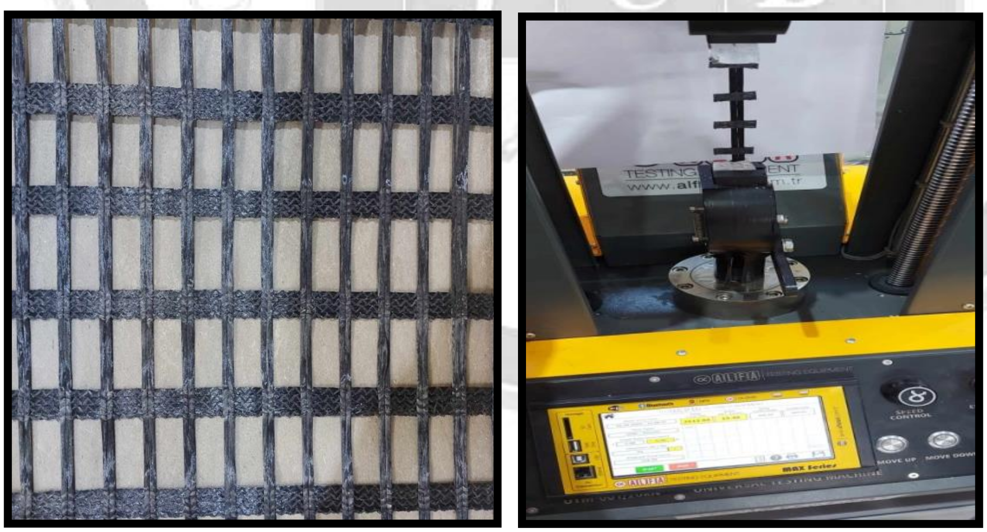


Figure (1) Testing process of geogrid mesh inside the lap

2.7 High Performance Mortar

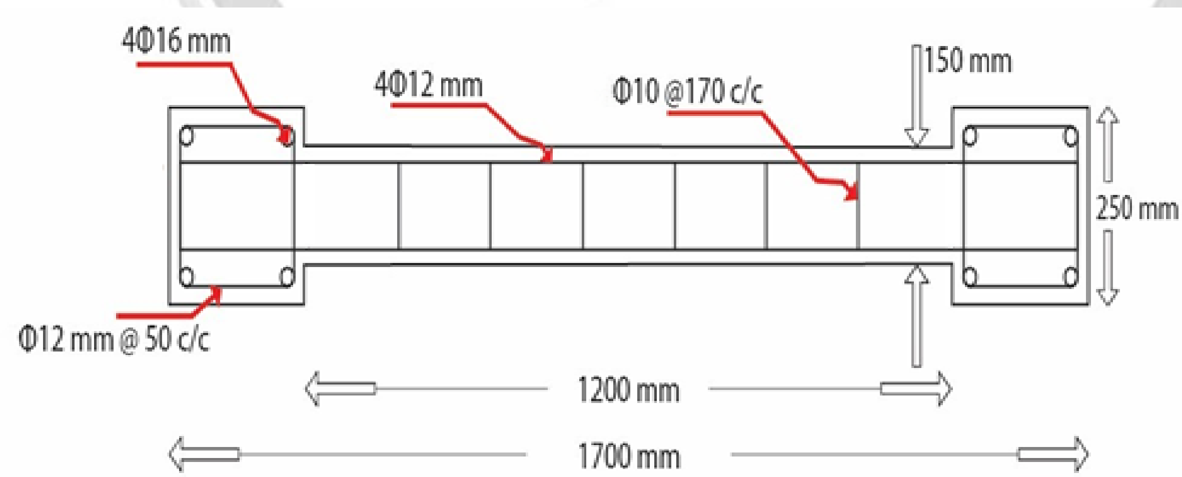
A ready-mixed mortar with modified specifications is used in ferrocement jacketing for the retrofitting of preloaded columns. It consists of a thin layer of bonding primer (Sika MonoTop®-610) and a layer of high strength mortar (Sika MonoTop®-612 IQ). This mortar includes Portland cement, well graded sand, synthetic fiber and selected additives required to improve its properties. It provides about (40) MPa of compressive strength at (28) days.

3. Specimen Details

Six reinforced concrete short columns with (150*150) mm cross section and (1700) mm in length are cast in steel molds. The columns have concrete brackets at each end with dimensions of (250*250*250) mm. Figure (2) shows longitudinal section of the reinforced concrete columns with cross sectional details. Two columns represented the control specimens and biaxially loaded till failure with (30) mm and (70) mm of loading eccentricity. The other four columns are preloaded up to (65) % and (85) % from the total failure loads of the control specimens and then retrofitted using ferrocement jacketing. This jacketing technique includes using of high performance mortar with two layers of geogrid mesh reinforcement. Description of the specimens according to their specific parameters used in this study is shown in Table (5).

Table (5) Description of the specimens.

Specimens	Eccentricity (mm)	Preloading (%)
C1-E30	30	…..
C2-E70	70	…..
C3-E30-L65	30	65
C4-E70-L65	70	65
C5-E30-L85	30	85
C6-E70-L85	70	85



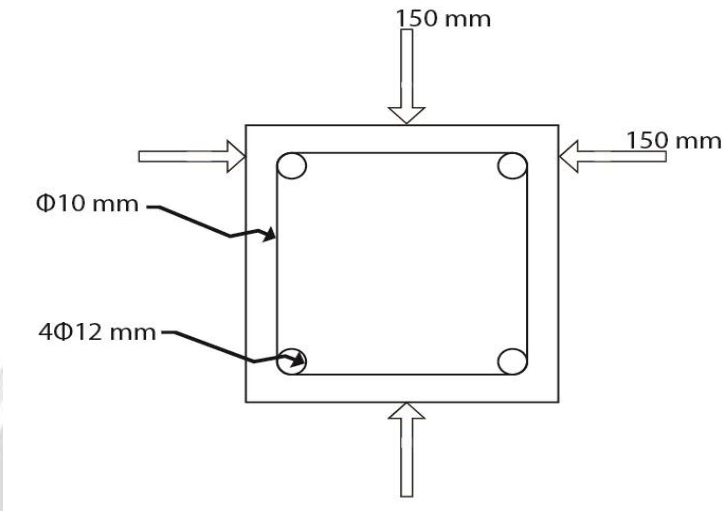


Figure (2) Longitudinal and cross sectional details of the columns

4. Retrofitting of the Preloaded Columns

As the two control specimens failed at (260) kN for column loaded with (ex = ey = 30mm) and (103) kN for column loaded with (ex = ey = 70mm). The other four columns are preloaded up to 65% which equals (169 kN and 67 kN) and 85% which equals (221 kN and 87.5 kN). Mild cracks appear at the tension zone of preloaded columns. Thickness of jacketing is (20) mm for all the retrofitted columns including the two layers of geogrid mesh reinforcement. Figure (3) shows the process of retrofitting for the preloaded columns. All the retrofitted columns are then biaxially loaded till failure after (28) days of curing.

Figure (3) Retrofitting of the preloaded columns

5. Testing Set-Up

Figure (4) shows the experimental set-up for the specimens. The testing machine consists of a (140 Ton) hydraulic operated jack connected with load cell and linear variable differential transducers (LVDT). The required information are presented through the attached data logger. Two steel brackets (each with 72.8 kg) are modified during the testing process at top and bottom of the columns in order to apply the eccentric loads through specific holes located at (30 and 70) mm away from the center for both axes (x and y). Features of ultimate carrying capacities, lateral load-displacement curves and crack patterns are the most observed results from this study.

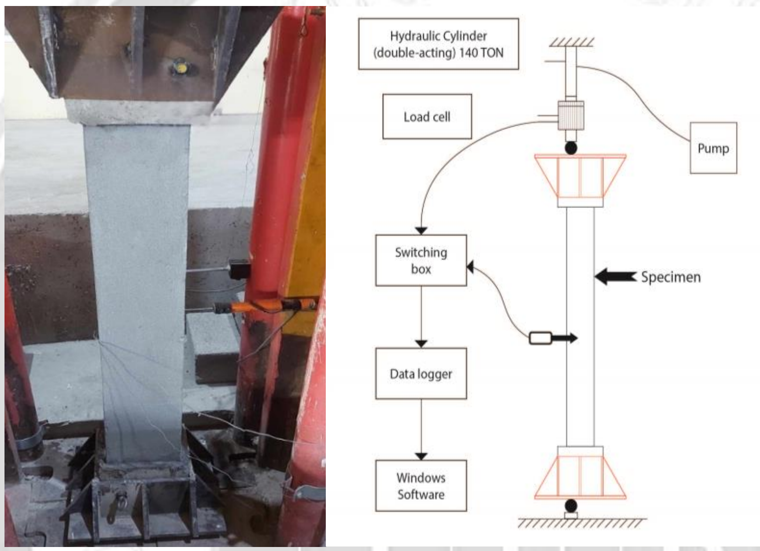


Figure (4) Testing set-up

6. Results and Discussions of the Experimental Work

6.1 Ultimate Carrying Capacity

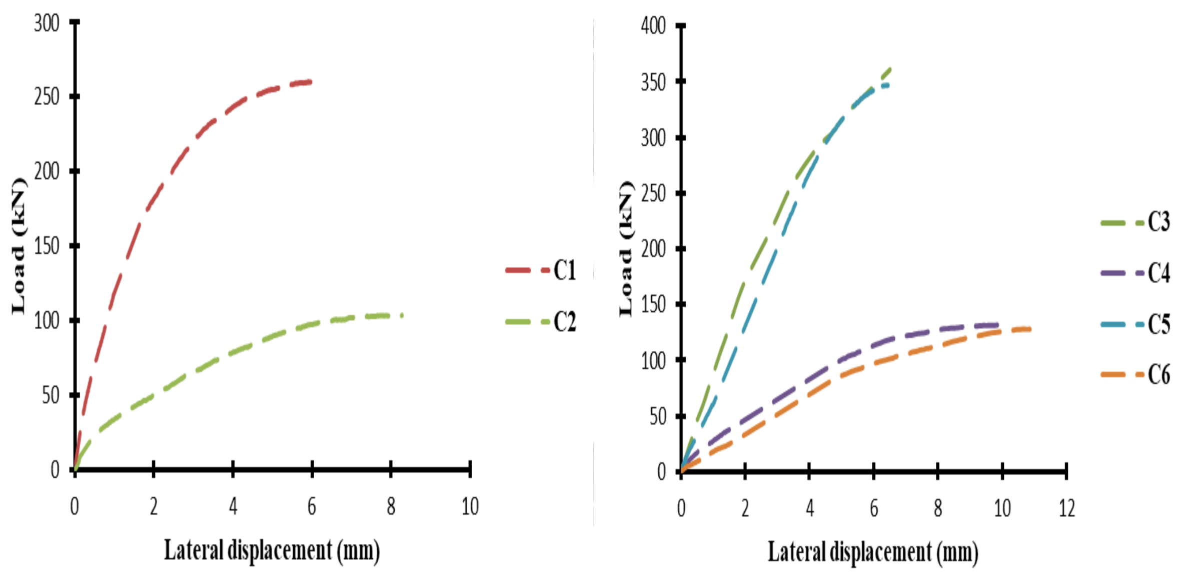
Table (6) presents ultimate carrying capacity for all the tested columns. It also shows the percent of enhancement for the retrofitted columns comparing to the control specimens based on the value of loading eccentricity. The two un-strengthened control specimens (C1 and C2) fail at (260 and 103) kN respectively. However, using of ferrocement jacketing with high performance mortar and geogrid mesh reinforcement significantly improve their performance at failure load. Columns (C3 and C5) with 30 mm of loading eccentricity recorded ultimate capacities of (360.8 and 346.7) kN. They enhance the capacity of control column (C1) by (38.8 and 33.3) %. Moreover, the carrying capacity of control column (C2) has increased to be (131.6 and 128) kN for the retrofitted columns (C4 and C6) with 70 mm of loading eccentricity.

Table (6) Ultimate carrying capacity for the tested columns.

Specimens	Ultimate Carrying Capacity (kN)	Enhancement (%)
C1-E30	260	…..
C2-E70	103	…..
C3-E30-L65	360.8	38.8
C4-E70-L65	131.6	27.8
C5-E30-L85	346.7	33.3
C6-E70-L85	128	24.3

6.2 Load-Displacement Curves

Figure (5) demonstrates load-displacement curves at mid-height of the control and retrofitted columns. Columns are in the elastic phase before cracking while the load and displacement are linearly related. Once the cracks appeared on the tension zone, the slope of curves decrease and develop nonlinearly. The mid-height displacement values at failure load for control columns (C1 and C2) are (5.91 and 8.28) mm respectively. However, the retrofitted columns (C3, C4, C5 and C6) have higher displacement values than the control specimens with (6.51, 9.86, 6.45 and 10.65) mm respectively. Increasing of the eccentricity from (30) mm to (70) mm creates additional bending moments on the columns which leads to produce higher displacement results.



ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلــة جـــامعة بـــــابـل للعلــــــوم الهندسية
Vol. 32, No. 4. \ 2024
ISSN: 2616 - 9916

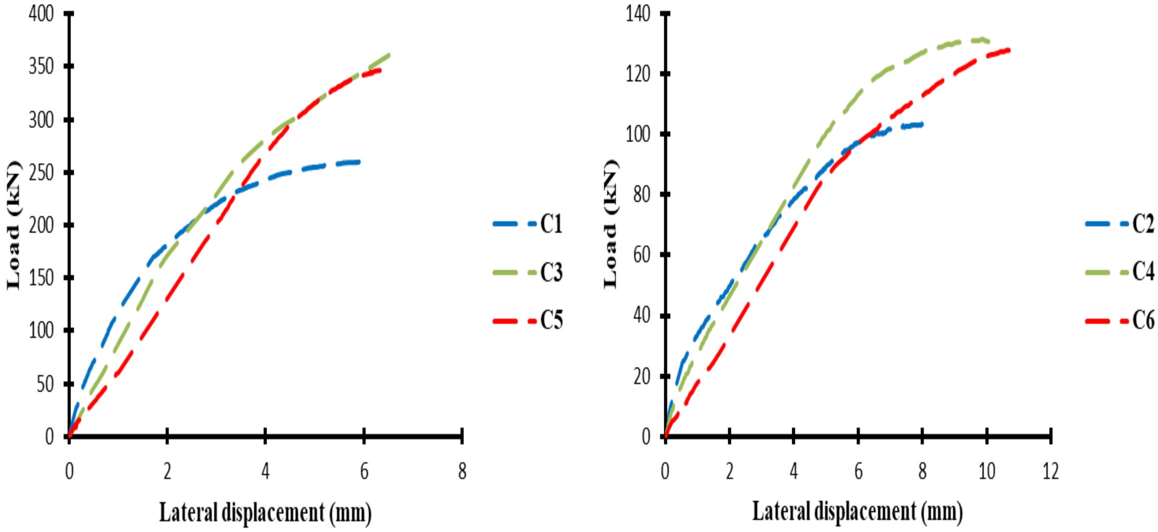


Figure (5) Load-displacement curves at mid-height of the tested columns

6.3 Crack Patterns

Figure (6) illustrates the crack patterns and failure modes for all the tested columns. The loading corner is called compression zone (CZ), and the corner on the opposite side of loading is called tension zone (TZ). Control columns (C1 and C2) failed through transverse cracks that appeared at the tension zone and extended to cause concrete crushing at the compression loading zone. However, all the retrofitted columns presented concrete crushing at the compression zone with some mild cracks at the corner of tension zone. The main crushing part in the loading corner was at the mid-span of the tested columns. Compared to the control columns without jacketing, ferrocement-jacketed columns exhibit fewer cracks at the tension zone. The retrofitted columns damaged by small eccentric compression with less development of cracks at their tension face and no clear signs appeared before failure.

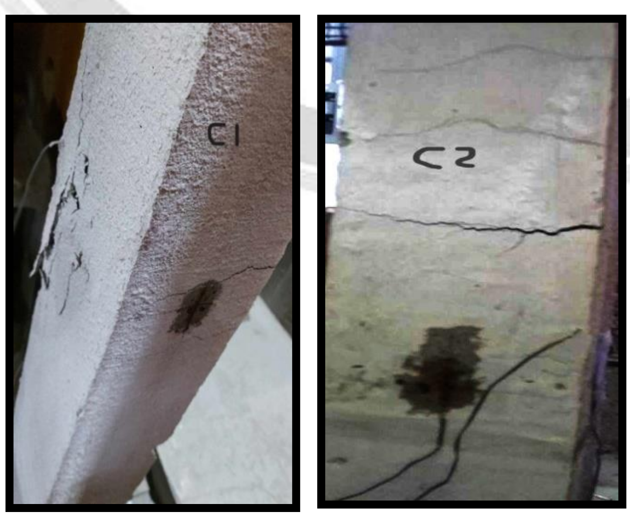


Figure (6) Crack patterns and failure modes for the tested columns

7. Analytical Study

Using ABAQUS program, the finite element analysis is applied to predict behavior of the retrofitted columns under biaxial loading conditions. Concrete damaged plasticity (CDP) is utilized to simulate the concrete properties in this study. The Plasticity parameters of concrete are mentioned in Table (7).

Geometry Modeling: Concrete is modeled as a three-dimensional solid element while all reinforcement bars and stirrups are modeled in wire element. Moreover, interaction between the reinforcement bars acting as embedded region and the concrete acting as host region is simulated using an embedded element. Figure (7) shows geometry modeling of the concrete columns.

Vol. 32, No. 4. \ 2024 ISSN: 2616 - 9916

Table (7) Plasticity parameters of (CDP) model.

Dilation angle ψ	**Eccentricity e**	fbo/fco	KC	**Viscosity μ**
35	0.1	1.16	0.667	0.006

Boundary Conditions: Both ends of the columns are considered as pinned to match the experimental conditions.

Loading: Two steps of loading are utilized, as 'step one' represents the preloaded percent before retrofitting with (65 or 85) % from the total failure loads of control specimens. While 'step two' is about applying loads until failure over the retrofitted columns. All the loads are eccentric with either ($e_x = e_y = 30$mm) or ($e_x = e_y = 70$mm).

Mesh: For the reinforced concrete columns used in this study, the following element types are assigned.

- C3D4: A 4-node linear tetrahedron used for the concrete.
- C3D8R: An 8-node linear brick used for mortar of the ferrocement.
- T3D2: A 2-node quadratic 3D truss used for the steel bars, steel stirrups and geogrid wire mesh.

Figure (8) shows the assembly mesh configuration for retrofitted model of a reinforced concrete short column using ferrocement consists of high performance mortar and geogrid mesh.

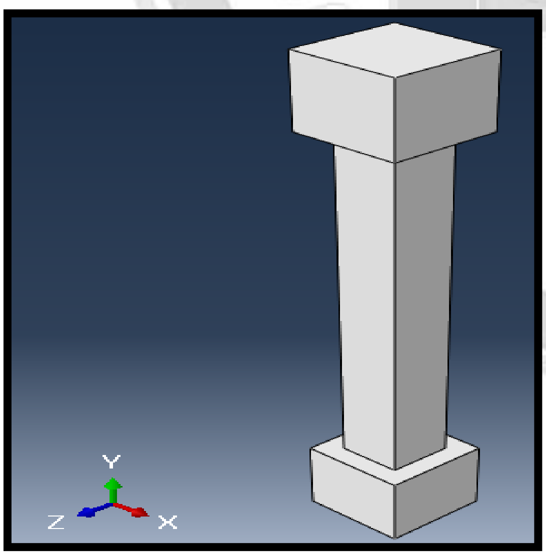


Figure (7) Geometry modeling

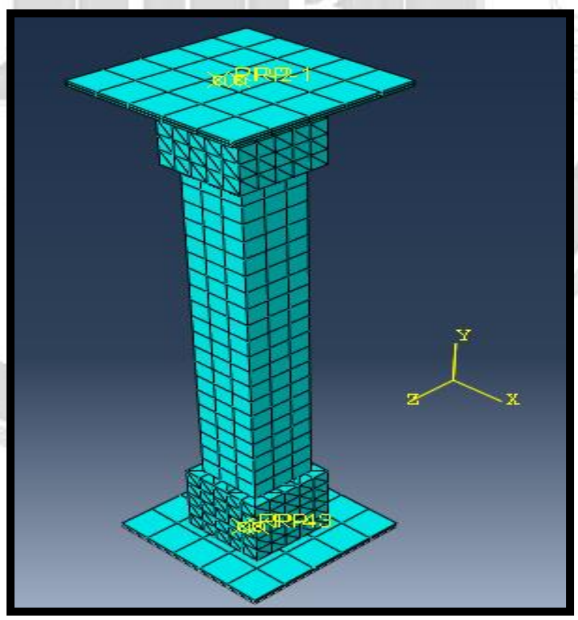


Figure (8) FEM mesh

8. Comparison Between Experimental and Analytical Results

8.1 Ultimate Carrying Capacity

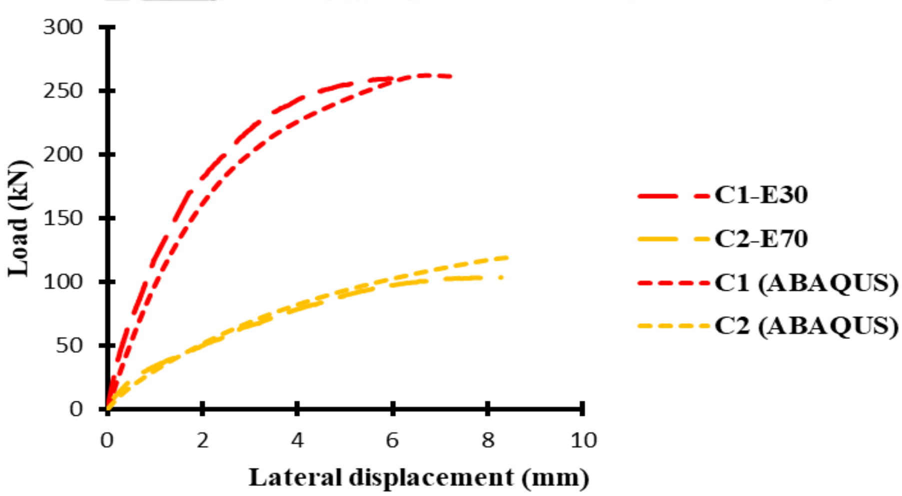
The comparisons in ultimate failure load between the experimental and theoretical results of the tested reinforced concrete columns are illustrated in Table (8). Slight differences among values of the both results are noted due to the fact that bonding between steel and concrete assumed to be full in the finite element modeling. Moreover, the theoretical analysis considers using of perfectly homogenous materials, while this concept is not available in the experimental work.

Table (8) Comparisons in ultimate capacity between experimental and theoretical analysis.

Specimens	Experimental Ultimate Load (kN)	ABAQUS Ultimate Load (kN)	Percent of Differences (%)
C1-E30	260	266.3	2.42
C2-E70	103	114.9	11.55
C3-E30-L65	360.8	375.4	4.05
C4-E70-L65	131.6	148.5	12.84
C5-E30-L85	346.7	359.3	3.63
C6-E70-L85	128	125.3	2.11

8.2 Load-Displacement Curves

The lateral load-displacement curves are obtained at mid-height of tension face for the tested reinforced concrete columns in both experimental and theoretical analysis. As shown in Figure (9), quite accepted results are obtained from the finite element analysis using ABAQUS and the practical tests. The theoretical results mostly produced steeper load-displacement curves than the experimental ones.



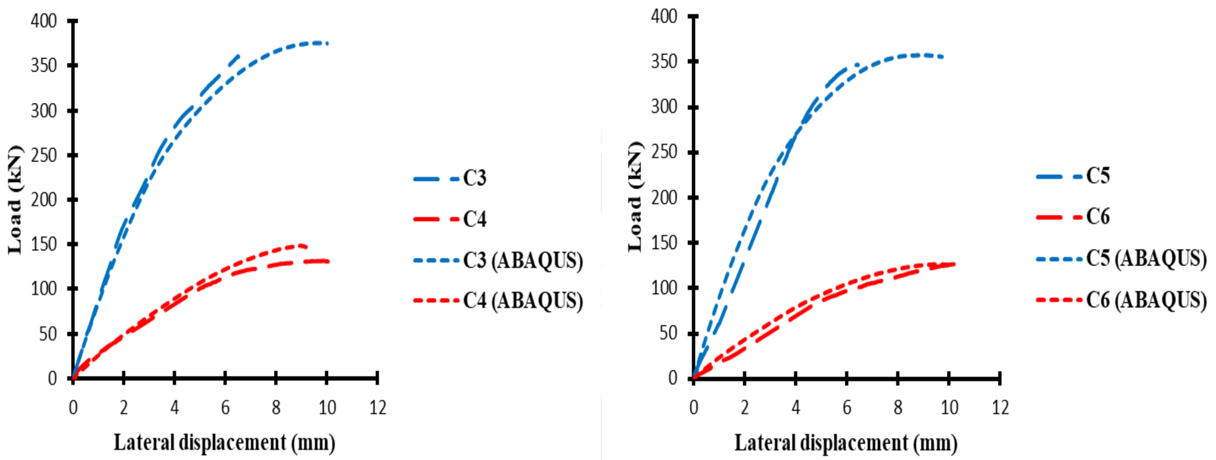


Figure (9) Experimental and theoretical load-displacement curves at mid-height of the tested columns

9. Conclusions

From the experimental and analytical results of the control and retrofitted reinforced concrete columns, the following points are concluded:

- Retrofitting of the preloaded columns using ferrocement jacketing with high performance mortar and geogrid mesh significantly increased their ultimate carrying capacities compared with the non-jacketed control columns.
- Column (C3-E30-L65) presents the highest enhancement in load carrying capacity with (38.8) %. However, column (C6-E70-L85) had the highest amount of mid-height lateral displacement at failure load with (10.65) mm.
- The eccentricity ratio produced an important impact on the specimens, as their ultimate capacity dropped when the eccentricity value increased. This is because the specimens with higher eccentricity exhibited larger lateral displacement and lower stiffness.
- The ultimate capacity of (65) % preloaded columns is always higher than columns with (85) % of preloading, as columns with lower ratio of preloading introduce higher efficiency of interaction with ferrocement.
- Using of high performance mortar had remarkable effects in the development of the ultimate capacity due to its higher material specifications and additives than the normal cement-sand mortar.
- The retrofitted columns (C3, C4, C5 and C6) are damaged by small eccentric compression with less development of cracks at their tension zone and no clear signs appeared before failure.
- A good agreement obtained between the experimental and analytical results in respect to the ultimate capacity and load-displacement curves.

10. References

[1] CPWD "Handbook On Repairs and Rehabilitation of RCC Buildings". Central Public Works Department, Govt. of India, India, 2002.

[2] Khan, S. U., Nuruddin, M. F., Ayub, T., & Shafiq, N., " Effects of Ferrocement in Strengthening the Serviceability Properties of Reinforced Concrete Structures", In Advanced Materials Research, Vol. 690, PP. 686-690, 2013.

[3] Aleksandra Nenadović, ŽikicaTekić, "Sustainability Benefits Of Ferrocement Application In Composite Building Structures", 5th International Academic Conference On Places And Technologies, Belgrade, Serbia, 2018.

[4] Paramasivam P, Lim CTE, Ong KCG., "Ferrocement application in structural upgrading-an overview", Journal of Structural Engineering ASCE, Vol. 32, No. 1 , PP. 27-31, 2005.

[5] Karthika, N. and Azhar, N. M., "Strengthening of RC column for retrofitting and rehabilitation by using ferrocement and wire mesh", MAT Journals: Journal of Structural and Transportation Studies, Vol. 2, No. 3, PP. 20-30, 2017.

[6] A. Kaish, Abdul Wahed, Rabiul Alam, "Behavior Of Ferrocement Encased Square Reinforced Concrete Column Under Eccentric Loading", International Conference on Structural Engineering and Construction Management, Sri Lanka, 2011.

[7] Akram S. Mahmoud, Sinan A. Yaseen, Samar S. Shafeeq, "Strengthening and Retrofitting of Reinforced Concrete Hollow Columns using High Strength Ferrocement Fibers Composites", Al-Nahrain Journal for Engineering Sciences (NJES), Vol.20, No.3, PP. 625-635, 2017.

[8] Mahmoud Elsayed, Alaa Elsayed, "Behavior of Biaxially loaded R.C. Columns Retrofitted by Ferrocement Jacketing", International Research Journal of Engineering and Technology, Vol. 5, No. 5, PP. 2007-2014, 2018.

[9] Fayzul Bari A., Amin A., Riyad R., Talukder L., "Strengthening of fire damaged reinforced concrete columns using ferrocement", Malaysian Journal of Civil Engineering, Vol. 33, No. 3, PP. 85-89, 2021.

[10] Iraqi Standard Specification I.Q.S., "Portland Cement". NO.5, 2010.

[11] Iraqi Standard Specification I.Q.S., "Aggregate of the Natural Sources Used in Concrete". NO. 45, 2010.

[12] American Society of Testing and Materials (ASTM) (1999b), "Standard Specifications for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement". West Conshohocken, USA.

[13] B.S 1881: Parts 116, British Standards Institute, "Method for Determination of Compressive Strength of Concrete Cubes". 1992.

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلــة جـــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 32, No. 4. \ 2024 ISSN: 2616 - 9916

دراسات تجريبية وتحليلية على الأعمدة الخرسانية المسلحة المحملة على محورين والمعاد تأهيلها باستخدام الفيروسمنت

هشام سالم مراد الراوي[1]* سفيان يونس احمد[2] سلوى مبارك عبدالله[3]

[1،2،3]قسم الهندسة المدنية، كلية الهندسة، جامعة الموصل، الموصل، العراق

salwa_hano@uomosul.edu.iq sofyan1975@uomosul.edu.iq hesham.salim@ntu.edu.iq

الخلاصة:

الأعمدة الخرسانية المسلحة والمحملة ثنائية المحور هي عناصر انشائية تتأثر بالضغط المحوري وقوى الانحناء في اتجاهين. تتضمن هذه الدراسة إعادة تأهيل الأعمدة الخرسانية المحملة مسبقًا باستخدام مادة الفيروسمنت التي تتكون من مونة عالية الأداء وشبكات تسليح جيوكرد. تم صب ستة أعمدة خرسانية قصيرة بأبعاد (150*150*1700) ملم مع دعامة خرسانية عند كل نهاية. اثنان من النماذج بمثابة أعمدة مرجع يتم تحميلها حتى الفشل، في حين تم تحميل الأعمدة الأربعة الأخرى بنسبة تصل الى (65 & 85)% من إجمالي أحمال الفشل لعينات المرجع مع اعادة تاهيلها. تغيرت قيمة انحراف التحميل بين (30) ملم و (70) ملم لكلا المحورين. أثبتت النتائج أن استخدام تقنية اعادة التاهيل هذه يزيد من قدرة التحمل القصوى للأعمدة المحملة بنسبة تصل الى (38.8)% مقارنة مع عينات المرجع. كما أنها تحسن من مقاومة الشقوق وسلوك الفشل. كذلك تم مقارنة النتائج العملية مع النتائج التحليلية النظرية التي تم الحصول عليها من تحليل العناصر المحددة باستخدام برنامج الأبوكاس.

الكلمات الدالة:- الأعمدة الخرسانية المسلحة، الفيروسمنت، شبكة الجيوكرد، تحليل العناصر المحددة، قدرة التحمل القصوى.