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Axial Compression Behaviour Of Repair And Strengthening Of Damaged Reinforced Structural Concrete Columns Using Hybrid Ferro Geopolymer Jackets

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Abstract
This research aimed at experimentally the efficacy of ferrogeopolymer jacketing for strengthening damaged reinforced concrete columns. Six column specimens (150×150×1500 mm) were subjected to axial loading 80% of their ultimate capacity to simulate varying degrees of damage. The damaged columns were then retrofitted using ferrogeopolymer jackets embedded with up to 3 layers of welded wire mesh (WWM) and expanded metal mesh (EMM). The load carrying capacity, axial deflection, and ductility indices of the retrofitted column specimens were assessed and contrasted with unconfined column specimen. The experimental ultimate load values were then corroborated by comparison with modified equations of ACI 318 and ECP 203. Regression analysis was performed to establish models between experimental and predicted results, and predicted results showed significant concordance with the experimental values. It was found that ferrogeopolymer jacketing columns substantially enhances structural integrity in terms of load carrying capacity, axial deflection and ductility indices, offering a viable alternative method for column rehabilitation.

1. INTRODUCTION

Maintenance and rehabilitation of reinforced structural components is perhaps one of the most critical problems in structural engineering field. Ferrogeopolymer confinement is relatively new class of non-corrosive, more durable, high strength, ductile, low cost and light weight materials that have been use from few decades emerged as secondary confinement for a variety of damaged structural components. Ferrogeopolymer are widely used due to low cost compared other retrofitting methods such as steel jacketing, reinforced concrete jacketing and Glass fibre Reinforced Polymer. Ferrogeopolymers however have relatively low modulus elasticity and durability concerns in acidic and alkaline nature. This research offers a great deal use of ferrogeopolymer wraps. Ferrogeopolymer application is superior way to repair and strengthened the damaged reinforced concrete structures that have become structurally weak over their life span. Ferrogeopolymer repair technique with source materials provides an economically viable alternative method to traditional repair methods. Ferrogeopolymer source materials provide specified properties to columns such as strength and stiffness. This source materials have high corrosion resistance and non-magnetic properties and low maintenance cost.They can easily be applied to existing damaged reinforced structural components and primarily improves concrete structure performance as it supplies lateral confining pressure to the existing concrete structure. Geopolymer source materials were found to be fire resistant under ultra violet rays. Presence high percentage of Ca(OH)2 content decreased the microstructural porosity and in turn improved mechanical properties such as compressive strength. Besides, the water to fly ash and GGBS ratio also influenced the mechanical properties. It was observed that as water to source material ratio decreased the compressive strength of the geopolymer mortar increased. The utilization of sodium hydroxide (NaOH) combined with sodium silicate (Na2SiO2) solutions in pre-defined ratios produced the highest compressive strength.

Geopolymer binders offers promising signs in producing high compressive strength. So seriously consider Geopolymer source materials as an alternative to cement. In every year billion of tons of fly ash and GGBS are produced worldwide by thermal power plants and steel plants respectively for satisfying the high demand in industrial and domestic area. The handling of this by-product source materials is always a matter of concern. Among the 20 billion tons only about 25-35% of the generated fly ash and GGBS are used, mainly as additive in concrete and cement binders and the rest of this disposed of. Therefore, effective strategies are needed to deal with this waste properly. Special attention should be concern to prevent environmental damage. In this regard, the synthesis of Geopolymer materials is an emerging approach.

2. MATERIALS

2.1 Cement

53 grade of OPC from Bharathi Cements Ltd., Telegana, India, was used in both concrete and mortar mixes.

2.2 Geopolymer Mortar (FA & GGBS)

Geopolymer mortar was formulated using fly ash (FA) and slag (GGBS) with equal quantities. Specific gravity of fly ash was 2.21, while GGBS 2.82. To ensure proper activation, these materials were sun-dried for 6 hours, mixed thoroughly, and oven-cured at 100°C for 24 hours before use.

2.3 Fine Aggregate

Clean, local available river sand was used as the fine aggregate with a specific gravity of 2.67 and FM of 2.44 and conforming to Zone 2 of IS 383.

2.4 Coarse Aggregate

Coarse aggregate with specific gravity of 2.80 and a FM of 6.80, ensuring good strength and durability. Conforming to specifications of IS 383:1970.

2.5 Superplasticizer

A high-performance superplasticizer, Armix Hyyecrete PC 20 was used in both concrete and mortar mixes.

2.6 Alkaline Solution

Alkaline solution was used in geopolymer mortar mix, with ratio of 2.5 between sodium silicate to sodium hydroxideis. NaOH solution was prepared with 12M molarity and was mixed 24 hours before use to ensure proper activation.

2.7 Steel reinforcement

High strength deformed steel bars Fe500 with a diameter of 12mm used as main reinforcement and 6mm diameter steel used as lateral ties in reinforced columns. EMM has an opening size of 19 mm × 33 mm × 2.1 mm. The ultimate tensile strength is 334 MPa. WWM consists of 12mm × 12mm × 0.75mm. its ultimate tensile strength is 598 MPa.

3. Experimental Programme

The response of damaged structural columns retrofitted with ferrogeopolymer jackets has been investigated through experimental programs involving axial compression testing. The present study involves six RC column specimens with dimensions of 150×150×1500 mm in two stages as follows; S1: Control column specimen where no preloading and ferrogeopolymer jackets, S2: Strengthened preloaded column specimens with ferrogeopolymer jackets after preloading them with 80% of their ultimate axial strength.

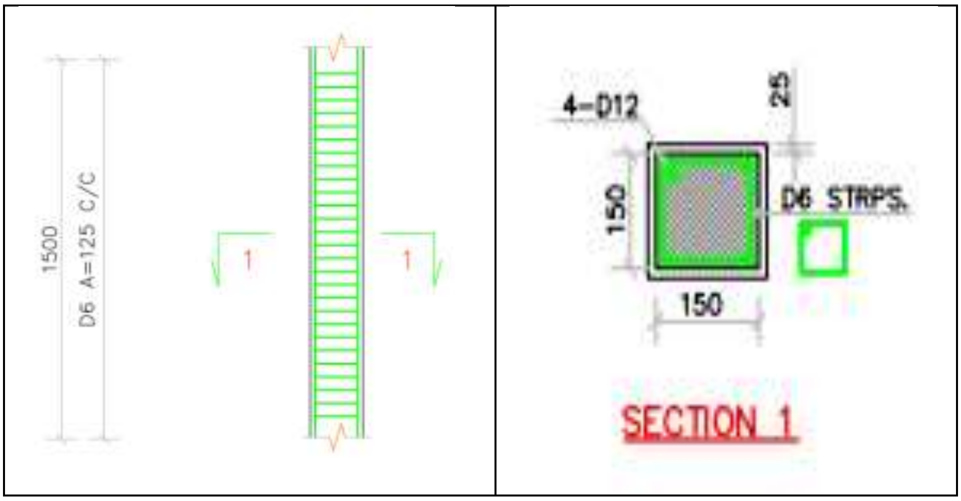


Figure 1: RC Column reinforcement details

The details and count of total columns were given in Table 1. Reinforcement details of column are shown in Fig. 1.

Table 1: RC columns

ID	Ferrogeopolymer jacketed column
CC	Conventional Column

FGE1	Damaged RCC retrofitted with 1 layer of Expanded Metal Mesh
FGE2	Damaged RCC retrofitted with 2 layers of Expanded Metal Mesh
FGE3	Damaged RCC retrofitted with 3 layers of Expanded Metal Mesh
FGW1	Damaged RCC retrofitted with 1 layer of Welded Metal Mesh
FGW2	Damaged RCC retrofitted with 2 layers of Welded Metal Mesh
FGW3	Damaged RCC retrofitted with 3 layers of Welded Metal Mesh

3.1 Preparation of Column Specimens

The longitudinal steel bars and transverse steel were prefabricated prior being placed into custom-designed horizontal steel moulds of size 150mm*150mm. Prior to positioning the reinforcement cage in the mould, the surface of the steel mould was coated with a releasing agent to facilitate easy demoulding. Wooden spacers of 15 mm thickness were strategically placed along the edges to ensure uniform concrete cover around the reinforcement.

To monitor axial strain behavior, strain gauges were installed at the intersection of main reinforcement of each column. Additionally, two strain gauges were connected to transverse reinforcement to measure strains in transverse reinforcement. These strain gauges were instrumental in ensuring proper vertical alignment throughout testing process, with readings used to minimize eccentricity.

The moulds containing the reinforcement cages were then positioned on a vibration table, where concrete was gradually poured while operating the table at a low speed to eliminate air pockets and ensure uniform compaction. Once casting, the columns were enclosed with wet burlap and stored in a controlled lab. Demoulding was performed after 48 hours, and columns were subsequently wrapped by damp cloths to maintain moisture for a curing period of 14 days.

In this study M25 concrete mix of 1:2.06:3.52 (cement: fine aggregate: coarse aggregate) was used. The mix contains 359 kg/m^3 of cement, 740 kg/m^3 of sand, and 1267 kg/m^3 of CA. A water-to-cement (w/c) ratio of 0.43 was maintained, with 154 kg/m^3 of water. Additionally, 3.53 kg/m^3 of chemical admixture was added to enhance workability. This mix gives a compressive strength of 35.58MPa at 28 days curing period.

3.2 Preparation of Ferrogeopolymer Jacketed Column Specimens

Ferrogeopolymer jackets were used to columns using WWM and EWM. Columns cast within moulds of size 170mm*170mm. The specimens were first preloaded 80% of ultimate axial load before jacket application.

To ensure a strong bonding for M25 concrete surface and geopolymer mortar, all column specimens were sandblasted before jacketing. Two horizontal strain gauges were attached to measure strain variations in the jacketed specimens.

The geopolymer mortar was prepared using fly ash (FA) and GGBS in a 50:50 ratio as the primary binders. The mix contained 362.06 kg/m^3 of fly ash, 362.06 kg/m^3 of slag, and 1086.20 kg/m^3 of clean river sand. The alkaline solution contains of 82.76 kg/m^3 of NaOH and 206.89 kg/m^3 of Na_2SiO_3, with a total alkaline solution of 289.65 kg/m^3. 72.41 kg/m^3 water was used to for workability and ensure proper mixing. The geopolymer mortar mix produced a 45.72MPa compressive strength at 28 days curing and a flow of 118%.

The geopolymer mortar mix was poured in 175mm*175mm mould around the 150mm*150mm column, while vibrating mould surfaces to ensure complete penetration and uniform encapsulation of the reinforcement layers. After casting, the top surfaces were finished smoothly and covered with damp cloths for two days. Upon demolding, the specimens were subjected to an additional 14-day curing period under moist conditions. Finally, the jacketed specimens were stored in the laboratory environment without further covering until the axial load tests were conducted.

3.3 Experimental instrumentation and test setup

Before testing, make sure that each column specimen was lined up both vertically and horizontally. Using engineering levels, the specimen's location was changed in the vertical plane until its centre line matches to resultant of the axial load. Using plumb bobs, the centre line of the specimen was lined up with the resultant axial load in horizontal plane. We employed a 10,000-kN hydraulic load to put the compressive load on the column. The strong floor was where the test assembly's column was put. To avoid eccentricity, the column was centered correctly with a plumb bob. The bottom end was put on the surface that didn't have any friction. Two dial gauge readings were employed to measure the lateral displacements in the column at a height of half the height. The dial gauges are linked to the side of the testing machine. We

used a Digital Electronic Strain Indicator to find out how much strain was in the concrete. An electronic strain indicator is connected to a strain gauge that is connected to the front of the column.
Key performance parameters evaluated include load-bearing capacity, axial deflection, deflection ductility index, and energy ductility index. These parameters provide insights into the performance of ferrogeopolymer jacketing in improving structural column lifespan. Experimental results of retrofitted columns were compared with conventional unretrofitted column and validated against existing design equations from ACI 318 and ECP 203 to assess the standard models in predicting the axial compressive nature of ferrogeopolymer-strengthened columns.

4. DISCUSSION ON TEST RESULTS

The compressive strength, deflection ductility and energy ductility of RC columns are critical parameters in evaluating their structural behaviour under axial loading conditions. This section presents the results of tested columns in terms of load carrying capacity, load vs deflection behaviour, deflection ductility index, energy ductility index, and failure mode.

4.1 Load carrying capacity

The mechanical properties of the all columns were assessed in 3 phases: first crack load, yield load, and ultimate load. The testing values of all column specimens were summarized in Table 2 and Figure 2. Conventional column exhibits an ultimate load of 606.54 kN, the traditional reinforced concrete column (CC) had the least load-bearing value at every stage. The columns' strength significantly improved after being retrofitted with ferropolymer (FG) meshes.Among all retrofitted specimens, FGW3 (3 layers of WWM) had the highest ultimate load of 1624.51 kN, which is almost 2.67 times higher than the CC column's ultimate strength. In other hand, FGE3 (3 layers of EWM) column gives an ultimate load of 1584.32 KN, which is equal 2.61 times higher than the CC column's ultimate strength This result gives that damaged reinforced columns retrofitting with multiple layers of ferrogeopolymer meshes considerably enhances load carrying capacity by improving its confinement and bolstering its resistance to crack propagation.

Table 2: Experimental values of columns

Column ID	FCL	DFCL	YL	DYL	UL	DUL	DDI	EDI
CC	101.12	1.93	351.79	5.42	606.54	13.78	2.54	19.84
FGE1	174.19	2.13	728.75	3.81	1325.09	13.14	3.44	20.82
FGE2	203.35	1.98	797.33	3.32	1398.84	13.94	4.19	29.48
FGE3	227.41	1.77	841.61	3.35	1584.32	14.08	4.2	32.06
FGW1	168.84	2.14	765.11	3.9	1442.33	14.64	3.75	21.74
FGW2	215.4	2.01	844.78	3.4	1456.79	13.18	3.87	26.27
FGW3	251.51	1.93	926.93	4.08	1624.51	15.97	3.91	31.31

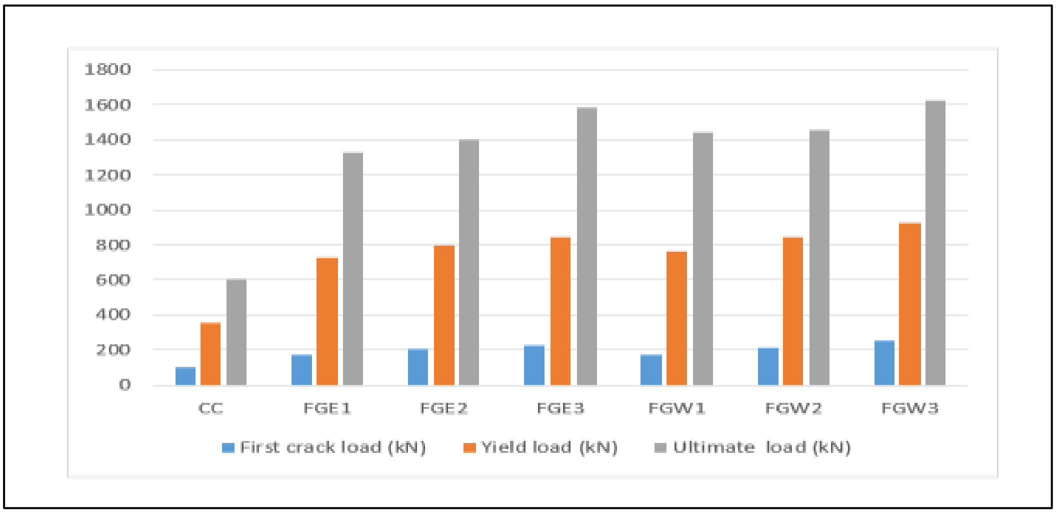
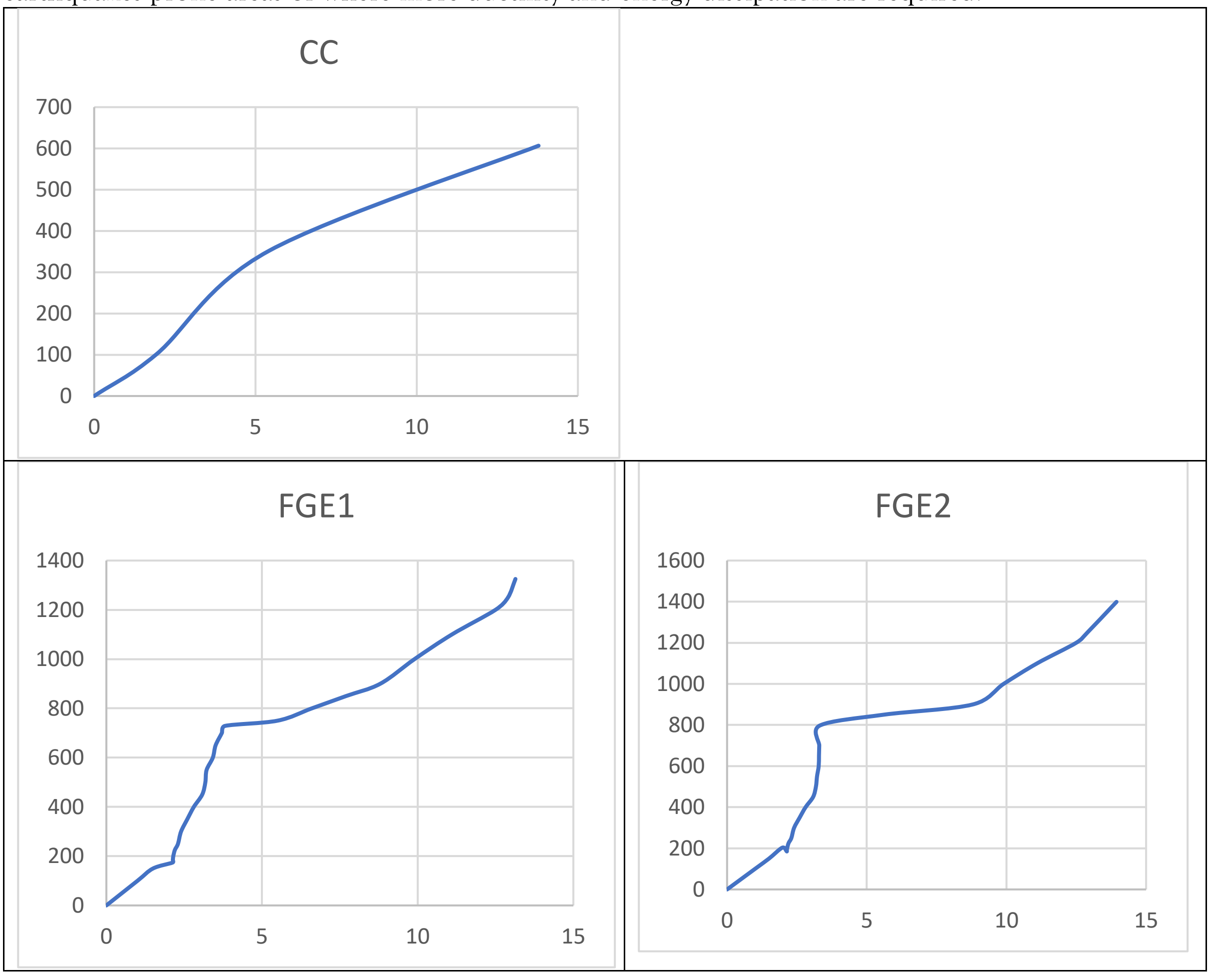


Figure 2: Results on columns testing

FCL: First crack load
DFCL: Deflection at first crack load
YL: Yield load
DYL: Deflection at yield load
UL: Ultimate load
DUL: Deflection at Ultimate load
DDI: Deflection ductility index
EDI: Energy ductility index

4.2 load vs deflection behavior

Figure 3 shows load vs displacement curves of all the columns loaded axially it is clear that how much the columns bent at the first crack load, yield load, and ultimate load. The unretrofitted column produce a deflection of 5.42mm and 13.78mm at yield and ultimate load respectively, which means it was brittle failure. On other hand retrofitted columns produce less yield deflections, which means that they become more stiffer when they were loaded. However, the final deflections were much higher, which means that it was ductile failure. However, columns wrapping with FGW3 exhibited highest ultimate deflection (15.97 mm), followed wrapping with FGW1 (14.64 mm) and wrapping with FGE3 (14.08 mm). From this results conclude that the wrapping with welded wire mesh columns was more flexible than the wrapping with expanded wire mesh columns, which meant that the retrofitted columns could bend more and more before they failure. This property is helpful in various structural applications especially earthquakes prone areas or where more ductility and energy dissipation are required.



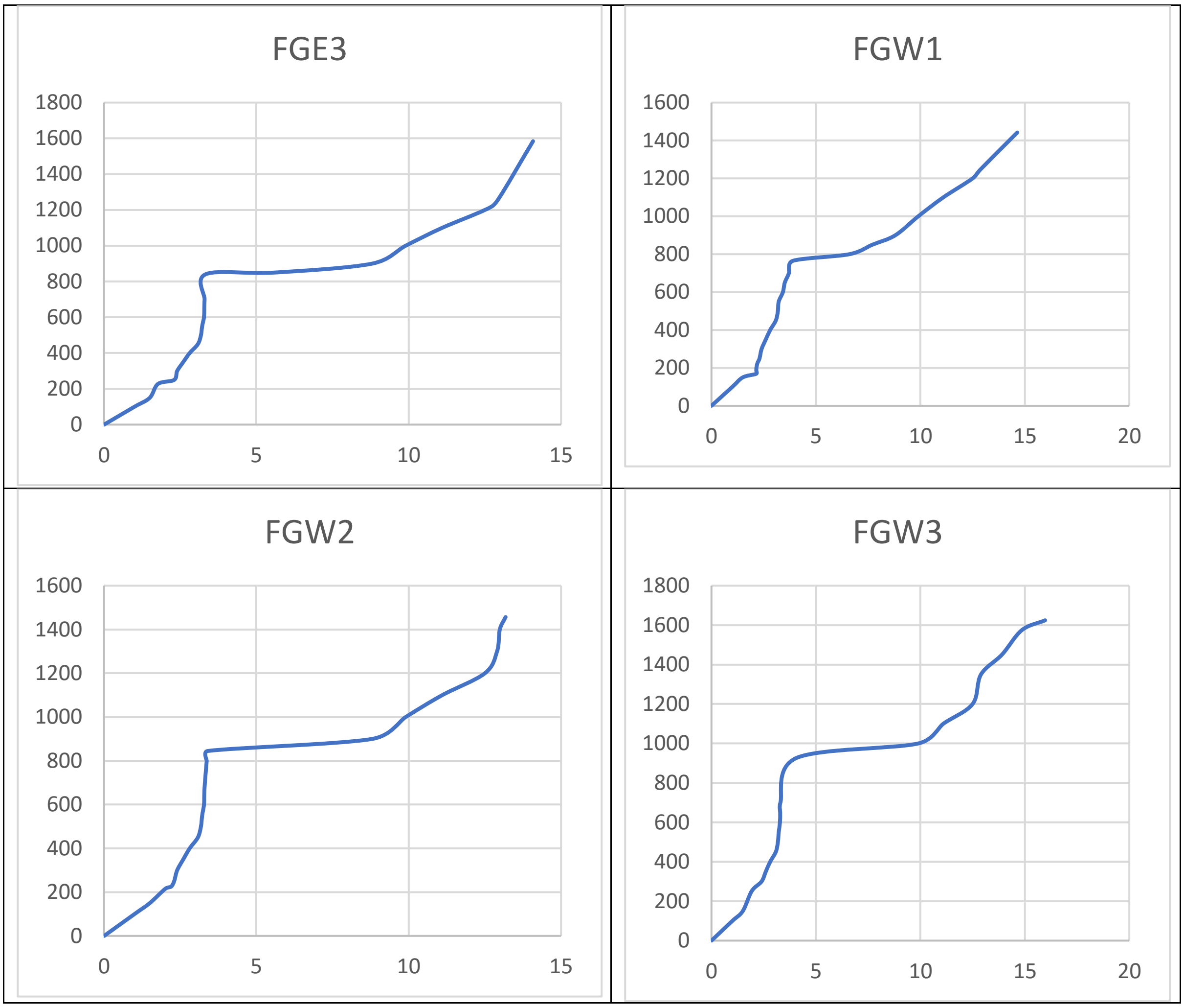


Figure 3: Load deflection behaviour of RC columns

4.3 Deflection ductility index

Deflection ductility index (DDI) defines it as the ratio of ultimate deflection to yield deflection. This parameter gives an idea, how well the column can bend without failure. The deflection ductility index values are presented in Table 2. The CC column had the lowest deflection ductility index 2.54, which means that failure mechanism of CC column was brittle. In other hand retrofitted columns had higher ductility index, wrapping with FGE3 having highest DDI value about 4.2, followed by wrapping by FGE2 about 4.19 and wrapping by FGW3 atbout 3.91. This means that expanded wire mesh is more flexible than welded wire mesh. This is likely because it can spread stress more evenly. The results show that adding ferrogeopolymer to columns makes them more flexible, which lowers the danger of sudden brittle failure and makes it easier for energy to be absorbed during loading situations.

4.4 Energy ductility index

The energy ductility index measures how much energy a column can take before it breaks. The deflection ductility index data are shown in Table 2. The CC column has the lowest energy ductility index of 19.84, which supports its brittle failure mode. The retrofitted specimens with the greatest energy ductility index were FGE3 (32.06), followed by FGW3 (31.31) and FGE2 (29.48). This means that columns with 3 layers of EWM absorbed the most energy before breaking, making them better for uses that need better impact resistance. Adding ferrogeopolymer layers to both expanded and welded mesh configurations made the material far better at absorbing energy than regular reinforced concrete.

4.5 Failure mode

The failure mode of CC column was sudden and brittle, characterized by the rapid formation of cracks and loss of load-carrying capacity. In contrast, the retrofitted columns exhibited a more controlled and ductile failure mode, with gradual crack propagation and improved post-peak behavior. The expanded wire mesh (FGE series) showed better energy absorption and ductility, which delayed crack widening and provided better crack bridging effects. The welded wire mesh (FGW series), particularly FGW3, demonstrated the highest load capacity and flexibility, making it an ideal retrofitting choice where both strength and deformation capacity are required. Overall, the failure patterns indicate that ferrogeopolymer mesh retrofitting enhances the resilience of damaged reinforced concrete columns, enabling them to sustain higher loads and deformations before failure.

5. Comparison of experimental results with theoretical results

Many standard codes of practice for the design of retrofitted columns have been published and practiced by various countries over the last two decades. The Modified Egyptian Code (ECP) Equation and Modified ACI 318 Code Equation are considered in this present study. The notations used in this thesis may differ from those used in the respective codes.

Many standard codes of practice for the design of retrofitted columns have been published and practiced by various countries over the last two decades. The Modified Egyptian Code (ECP) Equation and Modified ACI 318 Code Equation are considered according to [9] and [10] in this present study.

Equation for the Modified Egyptian Code (ECP)

Pu = 0.35 Ac fck + 0.67 As fy + 0.95 Ag fg + Ac N T .... (1)

Equation for the Modified ACI 318 Code

Pu = 0.85 Ac fck + As fy + 0.85 Ag fg + Ac N T .... (2)

The notations used in the above equations may differ from those used in the respective codes.

Where:

Pu = The column's Ultimate load
fck = Compressive strength of concrete.
fg = Compressive strength of GP mortar when it is compressed
fy = Steel's yield strength
Ac = Total area of concrete
Ag = Area of geopolymer mortar
Ac = Extra steel
N = Number of mesh layers
T = Tensile strength of meshes
As = Area of primary steel

The comparison between ultimate load results experimental dataset and theoretical dataset provides insight into the accuracy and applicability of different design codes for ferrogeopolymer-retrofitted columns. The experimental ultimate loads were evaluated against predictions from the Modified ACI 318 Code and the Modified Egyptian Code (ECP) using their respective equations. The ratios of experimental to theoretical values are presented in Table 3 (Pu^{Exp}/Pu^{th}).

Table 3: Comparison between experimental results Vs theoretical results

Column ID	P_u^{Exp}	P_u^{ACI}	P_u^{ECP}	P_u^{EXP} / P_u^{ACI}	P_u^{EXP} / P_u^{ECP}
FGE1	1325.09	1645.19	1250.28	0.81	1.06
FGE2	1398.84	1703.64	1308.73	0.82	1.07
FGE3	1584.32	1762.09	1367.18	0.90	1.16
FGW1	1442.33	1691.39	1296.48	0.85	1.11
FGW2	1456.79	1796.04	1401.13	0.81	1.04
FGW3	1624.51	1900.69	1505.78	0.85	1.08

The Modified ACI 318 Code results for FGE columns yield (PuExp/PuACI) ratios ranging from 0.81 to 0.90, and for FGW columns from 0.81 to 0.85. This suggests that the ACI-based model begins to overestimate the column capacity as the severity of damage increases. The increased cracking and possible microstructural degradation in the core concrete reduce its composite action with the retrofit system, leading to reduced actual strength compared to theoretical predictions. Although the ferrogeopolymer retrofitting still provides substantial recovery of load capacity, the assumptions made in the ACI model—

particularly regarding concrete confinement and residual strength—are less accurate under these higher damage conditions.
In comparison, the Modified ECP predictions at 80% damage become somewhat more accurate. The yield (PuExp/PuECP) ratios for FGE columns fall between 1.06 and 1.16, and for FGW columns between 1.04 and 1.11. This indicates a reduction in the conservative nature of the ECP model as the actual capacity of the columns also reduces. The theoretical values are still slightly lower than the experimental values. This behaviour implies that while ACI overpredicts at this damage level, ECP begins to match experimental results more closely, possibly due to its inherently lower assumptions for concrete and steel performance, which begin to reflect reality more closely as damage increases.

6. Comparison of experimental results with regression results

Regression analysis is a statistical technical tool for the examining the relation between two datasets called independent and dependent variables. The independent dataset and dependent dataset used regression analysis are given in Table 4 and 5.

Table 4: Independent variables for regression analysis

Column ID	fck	fg	fy	T	N
FGE1	35.58	45.72	488	334	1
FGE2	35.58	45.72	488	334	2
FGE3	35.58	45.72	488	334	3
FGW1	35.58	45.72	488	598	1
FGW2	35.58	45.72	488	598	2
FGW3	35.58	45.72	488	598	3

Table 5: Dependent variables for regression analysis

	FCL	DFCL	YL	DYL	UL	DUL	DDI	EDI
FGE1	174.19	2.13	728.75	3.81	1325.09	13.14	3.44	20.82
FGE2	203.35	1.98	797.33	3.32	1398.84	13.94	4.19	29.48
FGE3	227.41	1.77	841.61	3.35	1584.32	14.08	4.2	32.06
FGW1	168.84	2.14	765.11	3.9	1442.33	14.64	3.75	21.74
FGW2	215.4	2.01	844.78	3.4	1456.79	13.18	3.87	26.27
FGW3	251.51	1.93	926.93	4.08	1624.51	15.97	3.91	31.31

Table 6: Regression equations

Sl. No	Prediction Parameters	Regression Equation		R Square
1	FCL	fck	-3374.82	0.96
		fg	-1641.8	
		fy	390.4772	
		T	0.161638	
		N	16.68561	
2	DFCL	fck	-9.36074	0.89
		fg	-12.3776	
		fy	1.802058	
		T	0.000804	

		N	-0.22037	
3	YL	fck	-4348.7	0.91
		fg	-4205.4	
		fy	695.0844	
		T	0.427976	
		N	38.40692	
4	DYL	fck	62.22496	0.95
		Fg	-7.5017	
		fy	-3.73501	
		T	-0.00011	
		N	0.10453	
5	UL	fck	22049.13	0.99
		fg	10015.88	
		fy	-2482.35	
		T	-0.5105	
		N	220.4429	
6	DUL	fck	310.9508	0.97
		fg	-128.176	
		fy	-10.3823	
		T	-0.00047	
		N	1.094804	
7	DDI	fck	21.81153	0.92
		fg	-26.4653	
		fy	0.875055	
		T	-0.00017	
		N	0.200249	
8	EDI	fck	17.25638	0.93
		fg	-389.152	
		fy	34.38964	
		T	0.006222	
		N	3.7761	

Comparing the results of the experiment with those anticipated by regression gives us useful information about how well the regression model can estimate structural performance characteristics. The R^2 values in Table 6, which range from 0.89 to 0.99, show that there is a strong link between the experimental and projected values.

Figure 4 gives that the regression models are very close to the experimental values for all parameters such as all the loads and corresponding deflections and ductility indices. The scatter plots show linear relation between experimental values (shown as blue circles) are very close to predicted values by the regression model (shown as red crosses). There are small differences between the Deflection at Yield Load (DYL) and the Deflection at Ultimate Load (DUL). This shows that the model is good at predicting how things will bend. However, small changes in the Deflection Ductility Index (DDI) and Energy Ductility Index (EDI) show that additional factors, such as micro-cracking and irregularities in the material, could be affecting the outcomes of the studies. Even though there are some small differences, the regression model is still a good tool for predicting how structures will behave.

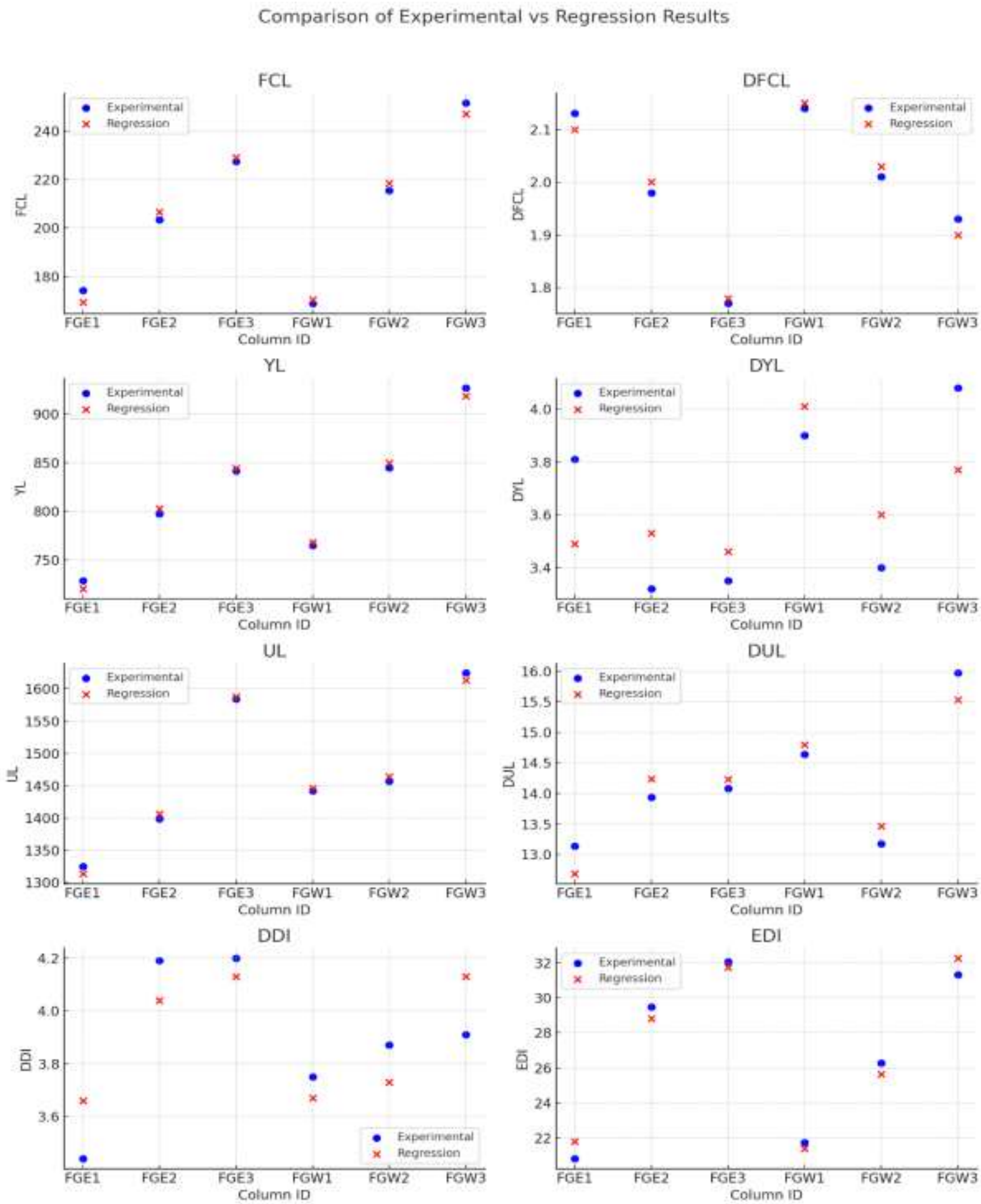


Figure 4: Predicted dataset vs Experiential dataset

7. CONCLUSIONS

The following main conclusions are drawn from this research are:

1. Columns retrofitted with ferrogeopolymer (FG) meshes showed substantial increases in load-carrying capacity, with FGW3 achieving 2.7 times the ultimate strength of conventional columns.
2. Retrofitted columns exhibited higher deflection ductility indices, with FGE3 having the highest value (4.2), indicating improved deformation capacity before failure.
3. Columns with three layers of expanded wire mesh (FGE3) absorbed the most energy before failure, making them more suitable for seismic applications.
4. Retrofitted columns exhibited ductile failure with gradual crack propagation, whereas conventional columns failed suddenly in a brittle manner.
5. Expanded wire mesh (FGE series) provided better ductility, while welded wire mesh (FGW series) offered higher load capacity and flexibility.

6. Theoretical predictions utilizing Modified ACI 318 closely aligned with experimental outcomes at 80% damage (Pu^{Exp}/Pu^{ACI} = 0.81–0.90), hence affirming the model's precision at reduced damage levels.
7. The Modified Egyptian Code (ECP) undervalued strength at 80% damage level (Pu^{Exp}/Pu^{ECP} = 1.04-1.11), owing to its conservative approach corresponding with actual deterioration
8. The regression model demonstrated strong correlations (R^2 between 0.89 and 0.99) with experimental results, proving its reliability in estimating load capacities and ductility indices.
9. While load predictions were highly accurate, ductility-related indices (DDI and EDI) showed minor discrepancies due to material variability and micro-cracking effects.

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