Behavior of Square Footings Reinforced with Glass Fiber Bristles and Biaxial Geogrid

El-Sayed A. El-Kasaby, Mahmoud Awwad, Mohab Roshdy, and Ahmed A. Abo-Shark

***Abstract* — This study investigates the influence of biaxial geogrids on the flexural behavior of square footing foundations reinforced with glass fiber reinforced concrete (GFRC). Experimental research is conducted, involving the testing of five reinforced concrete square footings under area loading until failure. The variables considered are the number of geogrid layers and the percentage of longitudinal reinforcement. Various parameters including deflection, loads at each stage, stiffness, ductility, energy absorption, crack patterns, as well as strains in steel, concrete, and geogrid, are analyzed and compared. The results reveal that incorporating geogrid layers as a reinforcement technique with GFRC significantly enhances the flexural behavior of the footings and improves cracking patterns. The number of geogrid layers used in the footings substantially increases the loads at each stage. Furthermore, an empirical equation is developed to establish a correlation between the moment acting on the footings and the tensile strength of geogrid reinforcement. The empirical evidence demonstrates a substantial improvement in the strength resistance of geogrid-reinforced footings with GFRC, surpassing those reinforced with steel and normal concrete mix. This research contributes valuable insights for the design and construction of earth structures, highlighting the advantages of biaxial geogrids in reinforcing GFRC footings with enhanced flexural performance.**

***Keywords* — Biaxial Geogrids, Flexural Behavior, Glass Fiber Reinforced Concrete (GFRC), Square Footing Foundations, Geogrid Reinforcement.**

I. Introduction

Geogrids, composed of polymers such as polyester, polypropylene, and polyethylene, play a crucial role in stabilizing soil and supporting critical civil infrastructure projects. Traditionally utilized for soil reinforcement, geogrids have also found applications in reinforcing asphalt layers and pavement networks. With their remarkable strength-to-weight ratio, cost-effectiveness, and ease of handling, geogrids have the potential to replace rigid pavements in various construction scenarios. Geogrids come in uniaxial, biaxial, and triaxial forms. Uniaxial geogrids are used for steep slopes and retaining walls, while biaxial and triaxial geogrids are common in roadways [1],[4]. The use of geo-grids to increase the bearing capacity of pavements, asphalt, and foundations has been widely focused on and explored. [5]. Geogrids have been effectively utilized to enhance soft subgrades and provide a construction platform over them [6], [7].

Recently, researchers investigated how the geo-grid may be used for concrete work [8]. Due to the more attention about geo-grid, either as longitudinal or transverse reinforcement bars, for RC members they have also begun to be used [9]. Because of geo-grid usability, it was efficient in a corrosive environment and less laborious. For the shear reinforcement, geogrid confinement may be an alternative solution. For effective transfer of tensile stress and for the enhancement of composite action of steel fiber reinforced concrete, the geo-grid with the usage of fiber may be a better choice [10]. Many studies also discovered that the geo-grid has a high efficiency in corrosive settings [11], [12].

Recent research has demonstrated the potential of Glass Fiber Reinforced Concrete (GFRC) in enhancing the strength and durability of concrete [13], [14]. GFRC, composed of minute fibers from natural or artificial sources, improves shear-friction strength, reduces crack propagation, and enhances ductility and toughness [15], [16]. Despite challenges related to fiber dispersion, combining GFRC with geo-grid reinforcement offers a viable substitute for traditional shear reinforcement, providing post-cracking tensile resistance to concrete beams while improving energy absorption capacity and ductility [17], [18].

The incorporation of geogrids as a reinforcement material in Portland cement concrete represents a novel application in the field of structural engineering. Limited studies have been conducted on the use of geogrids as reinforcement in thin members and overlays of Portland cement concrete [19]. Furthermore, there have been only a few research endeavors investigating the application of geogrids for enhancing the strength of concrete beams, slabs, and piles [20], [21].

This study focuses on investigating the flexural behavior of square concrete footings reinforced with geogrids. Two types of biaxial geogrids are utilized in glass fiber reinforced Concrete (GFRC) footings. Five footings undergo area loading and monotonic testing. Results reveal that geogrid inclusion notably enhances post-cracking ductility and strength, particularly in footings with multiple geogrid layers. Additionally, an empirical equation is derived to establish the correlation between footing moment and geogrid reinforcement tensile your paper.

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II. Experimental Application

A. Samples and Test Matrix

In the experimental program, a series of tests were conducted on five footings with different reinforcement configurations. Each specimen was carefully constructed to precise dimensions and subjected to specific loading conditions. The dimensions of each square footing were consistent, measuring (30 cm × 30 cm × 9 cm in thickness). A square loading plate of 7 cm × 7 cm was utilized. The footings were divided into five categories for the purpose of evaluating the effectiveness of various reinforcement methods, including a control specimen that incorporated steel reinforcement with reinforced concrete mix without glass fiber. Additionally, two specimens were reinforced with two layers of biaxial geogrid and GFRC, while the remaining two specimens were reinforced with three layers of biaxial geogrid and GFRC, Table I.

TABLE I: Test matrix

Group Name	Code of Specimen	Reinforced Material	Number of Units	Concrete Mixture
Control	C	Steel	2 @ 6 mm	Normal Reinforced concrete mixture (Without adding fiber bristles)
Group 1	Sq1	SS 30	2 layers	Glass fiber reinforced concrete (GFRC)
	Sq 2	SS 40	2layers	
Group 2	Sq 3	SS 30	3 layers	
	Sq 4	SS40	3 layers	

B. Reinforced Concrete Materials

In our experimental specimens, we employed ordinary Portland cement (OPC-42.5 grade), natural sand with a fineness modulus of 2.6, and filter stones with a maximum aggregate size of 9 mm. The reinforced concrete mix achieved a compressive strength (f_{cu}) of 28 MPa at 28 days, while the glass fiber reinforced concrete (GFRC) reached a strength of 32.26 MPa. The actual value of f_{cu} was determined on the day of testing. The concrete mix used for the GFRC maintained a consistent proportion of materials, supplemented with the addition of 2.5 kg/m^3 of glass fiber bristles provided by the CMB Group company in Egypt. These glass fibers had a length of 12-16 mm and a diameter of 12 microns, as detailed in Table II.

TABLE II: Concrete Mix Content by Weight for One Cubic Meter of (GFRC)

Material	Quantity
Cement (Kg/ m^3)	450
Sand (Kg/ m^3)	680
Water (Liter/ m^3)	215
Coarse aggregate (Kg/ m^3)	970
Glass fiber bristles (Kg/ m^3)	2.5

C. Footings Reinforcement

The control specimens in this study consisted of 6 mm diameter mild steel bars with a grade of 36 (yield stress: 36 Ksi) as primary reinforcement, shown in Fig. 1a. Biaxial geosynthetics geogrids (SS30 and SS40) by Tensar International Corporation were used, as depicted in Fig. 1b to Fig. 1e, with their mechanical properties documented in Table III.

D. Analysis of Soil Specifications

The soil used in this research conforms to well-graded gravel with sand classification according to unified soil classification system. Key indicators of soil grading include a uniformity coefficient of 22.50 and uniformity curvature of 1.98. The standard proctor test assessed compaction characteristics, revealing a maximum dry density of 2.078 t/m3 and optimum moisture content of 6.88%. A robust test tank, measuring 1.50 m (length), 1.50 m (width), and 0.70 m (height), constructed from durable steel (Fig. 2), were used as boundaries for soil layer.

TABLE III: Product Specification of the Biaxial Geogrids Used

Component of Biaxial geogrid			
Mechanical properties	Type of Geogrid		Unit
	SS30	SS40	
Max tensile strength	30	40	Kn/m
Tensile Strength at 2% Strain	10.5	14	Kn/m
Tensile Strength at 5% Strain	21	28	Kn/m
Approx. strain at max tensile strength	11	11	%

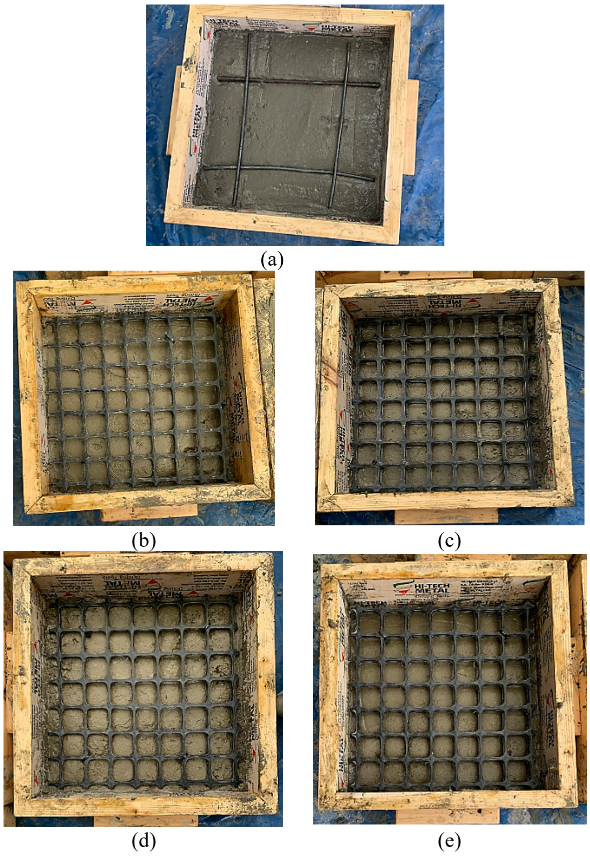

Fig. 1. Steel Bars and Biaxial Geogrids Used in the Study: a) 2 steel bars, 6 mm dia. in both directions; b) SS30, 2-layers; c) SS30, 3-layers; d) SS40, 2-layers; e) SS40, 3-layers.

E. Instrumentations and Test Set-Up

The samples were loaded using a hydraulic jack (max capacity: 1000 KN) connected to an electric pump, supported by a rigid reaction frame (max capacity: 1000 KN). Square footings were carefully placed on compacted soil, ensuring horizontal alignment for uniform stress distribution. Steel pallets (7 cm × 7 cm, 3 cm thickness) provided consistent load distribution. Load cells (max capacity: 1000 KN) measured vertical load, while five LVDTs monitored displacement. Test data were collected using a data acquisition system at two-second intervals.

Fig. 3 shows the setup at Benha Faculty of Engineering's concrete laboratory, University of Benha.

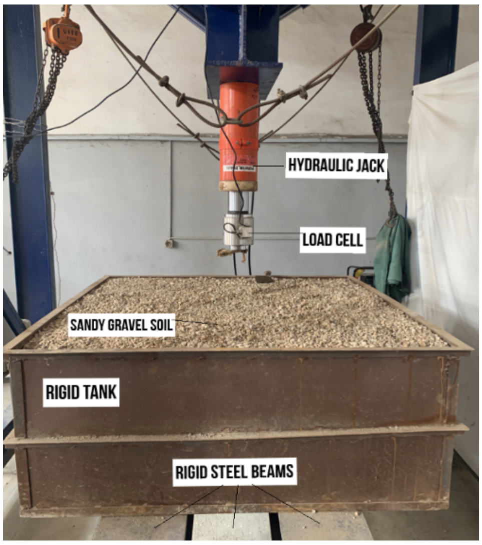

Fig. 2. Test Tank Configuration for Soil Layer Boundaries.

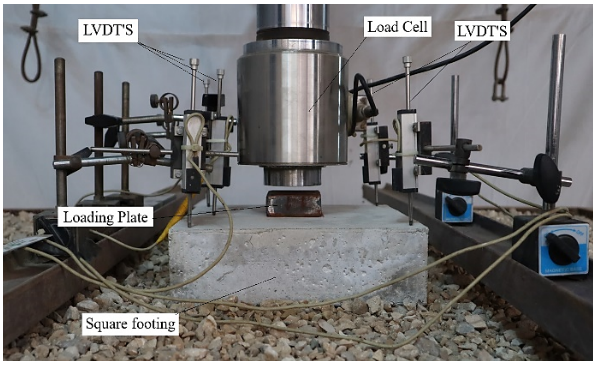

Fig. 3. Experimental Setup for footing specimen.

III. Results and Analysis

Fig. 4 illustrate the load-deflection behavior of square concrete footings reinforced with two and three layers of Biaxial geogrids. The load-bearing capacity (P), vertical displacement (Δ), and stiffness (K) were computed for all investigated footings at the first crack, yield, and ultimate stages based on the aforementioned figures. Additionally, the ductility (μ) and energy absorption (En) characteristics of each footing were determined. All the previous parameters are presented in Table IV.

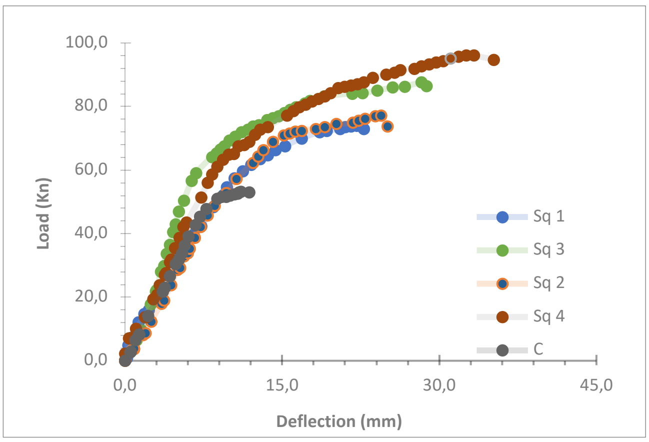

Fig. 4. Load-Deflection Behavior of Square Concrete Footings Reinforced with steel and Biaxial Geogrids.

A. *Examining Geogrid and Glass Fiber Bristles' Impact on Footing Behavior at Different Stages.*

1) *Load capacity at different stages*

It was found that the reinforcement footings by glass fiber bristles and geogrid would delay the onset of initial cracks and the post-crack behavior of the reinforcement footings demonstrated higher load-carrying capacities than the square footing (C), Fig. 5. As compared to a control footing, biaxial geogrid reinforcing with (GFRC) often results in gradual increases in the values of the cracking load (P_{fc}), yield load (P_y), and ultimate load (P_{ult}) as follows:

- P_{fc}, P_y and P_{ult} values at footings reinforced by two layers of biaxial geogrid SS30 increases by about 21.95%,34.45% and 39.01% respectively than for the concrete control footing (C1).
- P_{fc}, P_y and P_{ult} values at footings reinforced by two layers of biaxial geogrid SS40 increases by about 26.82%,35.07% and 45.07% respectively than for the concrete control footing (C1).
- P_{fc}, P_y and P_{ult} values at footings reinforced by three layers of biaxial geogrid SS40 increases by about 31.20%,48.43% and 64.56% respectively than for the concrete control footing (C1).
- P_{fc}, P_y and P_{ult} values at footings reinforced by three layers of biaxial geogrid SS40 increases by about 32.92%,61.98% and 80.54% respectively than for the concrete control footing (C1).

2) *Vertical displacement at different stages*

Compared to a control footing (C), footings reinforced by Biaxial geogrid and glass fiber bristles typically increases the values of vertical displacement at the yield stage (Δ_y) and ultimate stage (Δ_{ult}), as observed in the load-deflection curves as follows.

- Δ_y and Δ_{ult} values at footings reinforced by two layers of Biaxial geogrid SS30 increases by about 60.24% and 100.12% respectively than that for the concrete control footing (C).
- Δ_y and Δ_{ult} values at footings reinforced by two layers of Biaxial geogrid SS40 increases by about 63.95% and 121.19% respectively than that for the concrete control footing (C).
- Δ_y and Δ_{ult} values at footings reinforced by three layers of Biaxial geogrid SS30 increases by about 88.23% and 155.94% respectively than that for the concrete control footing (C).
- Δ_y and Δ_{ult} values at footings reinforced by three layers of Biaxial geogrid SS40 increases by about 113.17% and 201.60% respectively than that for the concrete control footing (C).

In the first crack stage, the vertical displacement values (Δ_{fc}) varied due to slight differences in soil compaction at the bottom of the footings. However, once the soil particles were properly distributed, the displacement behavior became more consistent as the load increased.

TABLE IV: PARAMETERS AND CHARACTERISTICS OF SQUARE CONCRETE FOOTINGS REINFORCED WITH STEEL AND BIAXIAL GEOGRIDS

	First crack stage			Yield stage			Ultimate load stage			Ductility factor (μ)	Energy absorption (kn/mm)
	P_f (Kn)	Δ_f (mm)	K_f (Kn/mm)	P_y (Kn)	Δ_y (mm)	K_y (Kn/mm)	P_u (KN)	Δ_u (mm)	K_u (Kn/mm)	-	
C	41.000	7.653	5.357	51.000	8.500	6.000	53.225	11.044	4.819	1.299	398.702
Sq 1	50.000	9.300	5.376	68.570	13.621	5.034	73.991	22.102	3.348	1.623	1179.953
Sq 2	52.000	8.700	5.977	68.889	13.937	4.943	77.216	24.429	3.161	1.753	1341.809
Sq 3	53.800	6.910	7.786	75.704	16.000	4.732	87.590	28.267	3.099	1.767	1922.899
Sq 4	54.500	7.300	7.466	82.611	18.120	4.559	96.097	33.309	2.885	1.838	2513.602

3) Stiffness of footing at different stages

When compared to a control foundation, footings reinforced by Biaxial geogrid and glass fiber bristles typically results in gradual decreases in the stiffness values at the yield stage (K_y) and ultimate stage (K_{ult}). This behavior was observed as the predominant characteristic of the samples. The results of the study are summarized as follows:

- K_y and K_{ult} values at footings reinforced by two layers of Biaxial geogrid SS30 decreases by about 16.09% and 30.53 % respectively than that for the concrete control footing (C).
- K_y and K_{ult} values at footings reinforced by two layers of Biaxial geogrid SS40 decreases by about 17.61% and 34.41 % respectively than that for the concrete control footing (C).
- K_y and K_{ult} values at footings reinforced by three layers of Biaxial geogrid SS30 decreases by about 21.14% and 35.70 % respectively than that for the concrete control footing (C).
- K_y and K_{ult} values at footings reinforced by three layers of Biaxial geogrid SS40 decreases by about 24.01% and 40.13 % respectively than that for the concrete control footing (C).

In the first crack stage, the stiffness values (k_{fc}) varied due to slight differences in soil compaction at the bottom of the footings. However, once the soil particles were properly distributed, the displacement behavior became more consistent as the load increased.

B. Effect of Geogrid and Glass Fiber Bristles on Displacement Ductility Behavior

In this research, we assessed the impact of geogrid reinforcement on the displacement ductility behavior of concrete footings. The displacement ductility index, a measure of the structural element's capacity to endure substantial deflections without significant strength reduction before failure, was utilized to evaluate the performance of the concrete footings. To ensure the resilience of concrete structures during seismic events, it is crucial for them to retain their strength above the yield strength, up to the permissible plastic deformation set in the design [22].

Our findings demonstrate that the incorporation of geogrid reinforcement can significantly enhance the displacement ductility behavior of concrete footings, Fig. 6. The displacement ductility indexes of the geogrid-reinforced footings were 24.88% to 34.90% higher for group 1, which had 2 layers of biaxial geogrid, and 35.96% to 41.47% higher for group 2, which had three layers of biaxial geogrid, compared to the control footings (C).

Our study also revealed a positive correlation between the increase in displacement ductility and tensile strength of the biaxial geogrids used. Moreover, increasing the number of geogrid layers did not negatively affect the behavior of the footings, as observed in the load-deflection curves. Therefore, incorporating multiple layers of biaxial geogrid reinforcement can be a practical and effective solution for improving the performance of reinforced concrete footings in weak soil conditions.

C. Effect of Geogrid and Glass Fiber Bristles on Energy Absorption [En]

A high capacity for energy absorption is beneficial in the event of major earthquakes, where substantial energy dissipation is necessary to prevent significant dynamic responses and hysteretic damping in concrete structures. The energy absorption capacity of the tested footings was determined by calculating the area enclosed by their load-deflection curves, as illustrated in Fig. 5.

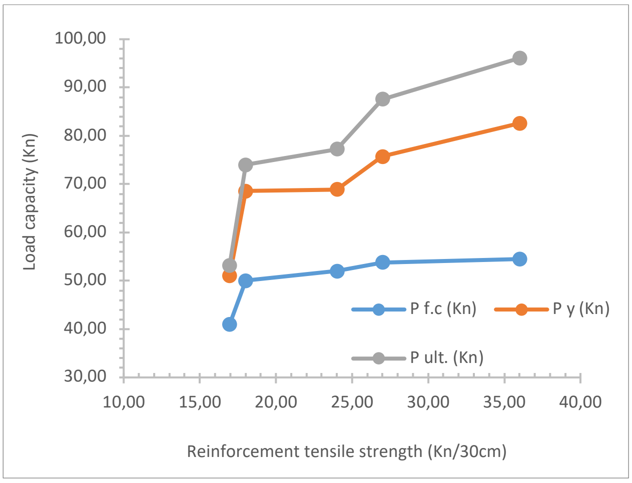

Fig. 5. Load capacity and total tensile strength relationship.

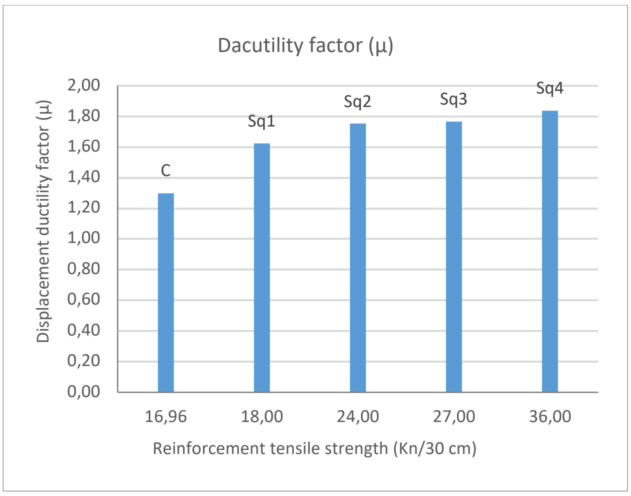

Fig. 6. Tensile Strength - Displacement ductility factor (μ) Relationship in Reinforced Footings.

In addition, the behavior of the tested footings was compared based on their energy absorption capacity and it was found that.

The energy absorption values of the geogrid-reinforced footings were 195.94% and 236.54% higher for group 1, which had 2 layers of biaxial geogrid, and 382.29% and 530.44% higher for group 2, which had three layers of biaxial geogrid, compared to the control footings (C) with a positive correlation to the stiffness and tensile strength of geogrid, Moreover, increasing the number of geogrid layers did not negatively affect the behavior of the footings, as observed in the result obtained, Fig. 7 depicts the relationship between the tensile strength of geogrid reinforcement and the corresponding increase in energy absorption for footings specimen.

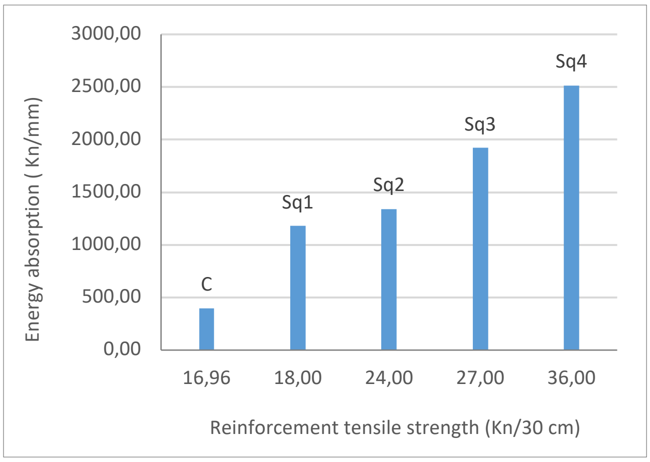

Fig. 7. Tensile Strength-Energy Absorption Relationship in Reinforced Footings.

D. Correlation between Square Footing Moment and Biaxial Geogrid Reinforcement

The research aims to explore the relationship between the applied moment on a square footing and the effectiveness of using biaxial geogrids as reinforcement. By analyzing various factors such as load distribution and geogrid properties. The findings of this analysis will contribute to a better understanding of the interaction between footing moments and geogrid reinforcement, aiding in the development of more efficient and reliable geotechnical design practices.

The calculation of the ultimate moment (Mu) and the required area of geogrid (Ag) for all groups of footings has yielded conclusive results. In order to establish a correlation between the ultimate moment (Mu) and the required area of geogrid (Ag) for different square footings (Sq 1 to Sq 4 for glass fiber reinforced concrete, GFRC), data-fit software was employed. This software allowed for the analysis of the relationship between Mu and Ag. The findings are presented in Fig. 8. Consequently, an empirical formula can be derived from these results as given in (1).

$$Ag = \delta * e^{\sigma * \frac{Mu}{d}} = N * L * T_{ult} \quad (1)$$

In the provided context, the variables in the equation have specific meanings. Here are their explanations:

- Ag: Total ultimate strength of the biaxial geogrid on the footing (Kn/m).
- Mu: Ultimate moment exerted on the footing (Kn.m).
- d: Depth of the square footing (m).
- δ: Value of 2.6304.
- σ: Value of 0.003.
- N: Number of geogrid layers.
- L: Length of geogrid within the footing (m).
- T_{ult}: Tensile strength of the biaxial geogrid used (Kn/m).

These points provide a concise overview of the variables and their respective meanings.

E. Failure Pattern

In all tested concrete footings, the occurrence of cracks was limited to a perpendicular orientation to the load plate, resulting in flexural cracks without any shear cracks.

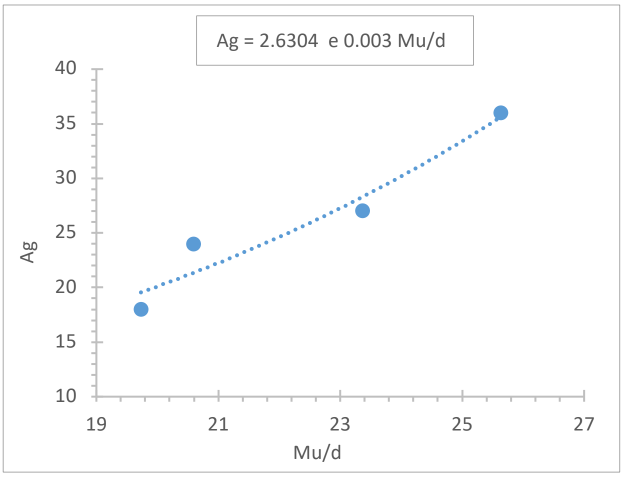

Fig. 8. Correlation between Ultimate Moment (Mu) and Required Area of Geogrid (Ag) for Different footings.

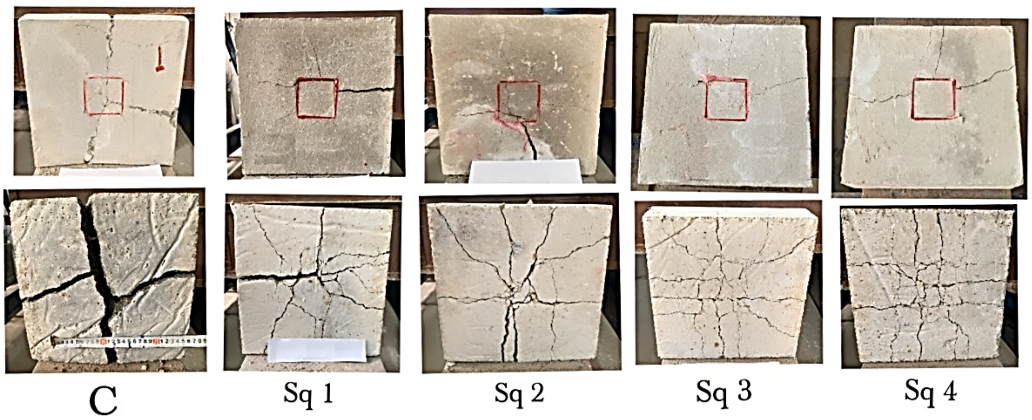

Fig. 9. Crack Patterns Observed in Concrete Footings.

The failure mechanism of the concrete footings was characterized by crack widening, the formation of additional cracks in some footings, and the propagation of these cracks from the tension zone (bottom surface of concrete) to the compression zone (top surface of concrete) until failure. The crack patterns observed in the footings are visually depicted in Fig. 9.

In the control concrete footing (C), four prominent cracks formed and gradually expanded until failure. These cracks exhibited significant thickness and indicated substantial damage to the steel bars at the failure load. Conversely, in group one and two, numerous smaller cracks appeared in various directions. These cracks were considerably narrower, and their density decreased more prominently in the footings reinforced with three layers of geogrid compared to those reinforced with two layers. Notably, no cutting of the ribs of the Biaxial geogrids was observed. Overall, the damage observed in the samples reinforced with biaxial geogrids was significantly less severe than that observed in the control samples.

Hence, a positive correlation can be observed between the number and thickness of flexural cracks, the tensile strength of geogrids, and the number of geogrid layers.

IV. Conclusion

1. In conclusion, the research findings demonstrate that the inclusion of glass fiber bristles and biaxial geogrid reinforcement significantly improves the load-carrying capacity of footings. The enhancements observed range from approximately 24% to 82% for cracking load (P_{fc}), 35% to 64% for yield load (P_y), and 42% to 82% for ultimate load (P_{ult}) compared to the steel reinforcement footings. These results highlight the substantial improvements in structural performance achieved through the reinforcement method.
2. The inclusion of Biaxial geogrid and glass fiber bristles in footings significantly increases the vertical displacement values at the yield stage (Δ_y) and ultimate stage (Δ_{ult}), with increases ranging from approximately 60% to 201% compared to the control footing (C).
3. The incorporation of Biaxial geogrid and glass fiber bristles in footings typically results in gradual decreases in stiffness values at the yield stage (K_y) and ultimate stage (K_{ult}), with reductions ranging from approximately 16% to 40% compared to the control footing (C).
4. Geogrid reinforcement significantly enhances the displacement ductility behavior of concrete footings. The inclusion of two or three layers of biaxial geogrid increases the displacement ductility indexes by approximately 25% to 42% compared to the control footings. This improvement highlights the effectiveness of geogrid reinforcement in enhancing the capacity of concrete footings to withstand substantial deflections without compromising their strength.
5. Geogrid reinforcement significantly enhances energy absorption in footings. Two or three layers of biaxial geogrid yield energy absorption values approximately 196% to 530% higher than the control footings. Geogrid reinforcement is a reliable and effective approach for boosting energy absorption in footings.
6. The use of biaxial geogrids as reinforcement in concrete footings resulted in a significant reduction in the number and width of flexural cracks, indicating improved structural performance and durability.
7. An empirical formula was developed to establish a relationship between the ultimate moment (Mu) and the required area of geogrid (Ag) for square footings.

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