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Behaviors of isolated footings reinforced with glass fiber bars

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ملخص البحث

اساسات المنشأ هى ذلكَ الجزء الذي يتصل مباشرةً بالتربة حيث تتألف المنشآت من عدة عناصر والتي تعمل معاً لتحمل الأحمال التي يعرض لها المنشأ وتوصيلها بأمان إلى التربة. وعلى وجه العموم فإن الأحمال التي تتعرض لها المباني تنتقل من البلاطات إلى الكمرات والتي تنقلها بدورها إلى الأعمدة ومن ثمّ إلى القواعد والتي تعمل على نقل تلك الأحمال وتوزيعها على تربة التأسيس وقد يوجد أنواع اخرى من اشكال توصيل الأحمال الى الأساسات طبقاً لنوع النظام الإنشائي فعلى سبيل المثال قد تنتقل الأحمال مباشرةً من البلاطات اللا كمرية إلى الأعمدة وقد تتصل الأحمال مباشرةً بالأعمدة كأحمال المصاعد والأحمال الأفقية كأحمال الرياح. وبناءًعلى ذلك يتلخص دور القواعد فى المنشآت في توصيل الأحمال الرأسية والأفقية والعزوم وكافة أشكال الأحمال من الجزاء العلوية للمنشأ وتوزيعها بأمان على تربة التحميل بشكل يضمن قدرة التربة على تحمل تلك الأحمال كما تعمل أيضا كركائز لتلك المنشآت لتضمن ثباتها واتزانها وعدم دورانها وانقلابها أو إنزلاقها.الاسياخ المصنوعة من البوليمرات المسلحة بألياف الفيبر لها خواص فيزيائية وميكانيكية مختلفة عن صلب التسليح التقليدي. في هذه الدراسة الحالية تم اختبار أربعة قواعد مربعة مسلحة بالاسياخ الحديدية والاسياخ ابوليمرية المسلحة بالالياف الزجاجية. ابعاد العينات المختبرة تم اختيارها لتكون تقريبا من 2/1 الي 3/1 من الأبعاد الشائعة للقواعد المعتاد استخدامها في المباني متوسطة الإرتفاع. كل القواعد المختبرة لها نفس العمق 170 مم ونفس الأبعاد 900 مم * 900 مم .ومن نتائج الإختبار وجد أن قدرة تحمل القواعد الخرسانية المسلحة بالأسياخ المصنوعة من الألياف الزجاجية لا تختلف كثيرا عن نظيرتها المسلحة بالأسياخ المصنوعة من صلب التسليح التقليدي.

Abstract

Foundation is that part of the structure, which is in direct contact with soil. The R.C. structures consist of various structural elements that act together to resist loads and transfer them safely to the soil. In general, the loads applied on buildings are transferred from slabs to beams, and then beams transmit them to the column, after those columns conveying loads to the soil through the foundation. There are other forms of load transfer. Footings transfer the vertical and horizontal loads, Moments, and all forces to the soil. Therefore, the important purposes of the foundation are to transfer forces from superstructure to soil below, to distribute stresses on foundation soil, and to develop a stability anchor against overturning. FRP bars have different physical and mechanical properties compared with those of steel bars. In the present study, a total of four square footings reinforced with steel and glass FRP bars were tested. The dimensions of the test specimens were chosen to be approximately equal to (1/2:1/3) of the size of common footings usually used in medium height buildings. All tested footings had the same depth of 170 mm and the same footprint of 900 mm x 900 mm. From the test results, it can be found that the ultimate capacity of punching shear for footing specimens reinforced with GFRP bars was slightly similar to that for footing specimens reinforced with steel bars.

Keywords:

Isolated footings; glass fiber bars; FRP; failure mode; foundation; punching

Introduction

The corrosion that occurs as a result of aggressive environments is a big problem in Structural Engineering. The high costs of repair and maintenance of structures damaged by corrosion led to the development of a new concrete reinforcing material. With the high strength and corrosion resistance of the fiber-reinforced polymer (FRP) bars, they represent a promising alternative to steel reinforcement. Where footings are located below the ground level, they are exposed to aggressive environments more than any other element of the structure. In addition, it is so difficult to be repaired. Therefore, the use of (FRP) bars as an alternative concrete reinforcing material in the reinforced concrete footings has great importance worth studying to improve the reinforced concrete structures' performance and to prevent the complicated and expensive prospective repair techniques. On the other hand, one of the most important deficiencies of using a fiber-reinforced polymer as reinforcement material of reinforced concrete structural elements is the high coefficient of thermal expansion perpendicular to the fibers relative to concrete. That does not represent a big deal when we use it as a reinforcement material for reinforced concrete footings because they are embedded in the soil far away from the effect of the fire's high temperature.

There is a huge effort being made by researchers on the durability of FRP bars and to investigate the behavior of concrete elements reinforced with FRP. Therefore, several codes were developed to address the design procedures for the concrete members reinforced with FRP bars. Several codes and design guidelines for concrete structures reinforced with FRP bars are currently available such as ECP 208-2005, ACI 440.1R-15, CSA-S806-02, JSCE, 1997, and CNR-DT-203. The flexural and shear behavior of column footings in the standing codes and guidelines is mostly based on experiments performed on reinforced concrete slabs. The effects of different parameters on the behavior of steel reinforced concrete footing have been investigated, but not appropriately. (Mikael Hallgren et al. (1998) [1], Hegger et al. (2007) [2], Josef Hegger et al. (2009) [3], Zoran et al. (2012) [4], Carsten Siburg, and Josef Hegger (2014) [5], João T. Simões et al. (2016) [6], Santos et al. (2018) [7], Dominik Kueres et al. (2018) [8]). On the other hand, the information on the behavior of FRP reinforced concrete footings is relatively limited due to the lack of analytical and experimental studies. Only two research studies have been done to study the behaviour of FRP reinforced concrete footings (Mohammad P. Kivi et al. (2012) [9], Asghar et al. (2017) [10]).

FRP bars have different physical and mechanical properties than those of steel bars, such as their linear stress-strain behavior until rupture and their relatively low modulus of elasticity. Their lower stiffness in comparison with steel bars, resulting in a large strain, which leads to large deflection and wide deep cracks. Therefore, the behavior investigation of FRP reinforced concrete elements needs more research effort to evaluate the design requirements of concrete structures reinforced with FRP bars especially reinforced concrete footings, which did not get enough attention from researchers.

With the lack of experimental test results related to FRP-reinforced concrete footings, an experimental investigation including isolated concrete footings reinforced with GFRP bars was performed to enhance a better understanding of the behavior of isolated concrete footings reinforced with GFRP bars. This investigation explores the behavior of R.C footings reinforced with FRP bars in normal strength concrete. The experimental results of this study contribute to the current knowledge of GFRP-RC footings, and the global experimental database of the behavior of FRP reinforced concrete members without shear reinforcement.

Experimental program

Specimens' characteristics

In the present study, a total of 4 square footings with square column stubs were tested. The dimensions of the test specimens were chosen to be approximately equal to (1/2:1/3) of the size of common footings usually used in medium height buildings. All tested footings had the same depth of 170 mm, a constant concrete cover of 35 mm, and a constant footprint of 900 mm x 900 mm. Column stubs were of 150 * 150 mm cross-section and 150 mm height. All square column stubs were cast monolithically at the Centre of the slabs. The test parameters investigated were the reinforcement bars type (FRB bars and steel bars) and the reinforcement ratio. All tested specimens had the same concrete strength (Fcu) of 32 MPa. To present the effect of Soil-structure interaction, all footings were realistically supported on a sand bed. The specimens were divided into two series (GF and SF).

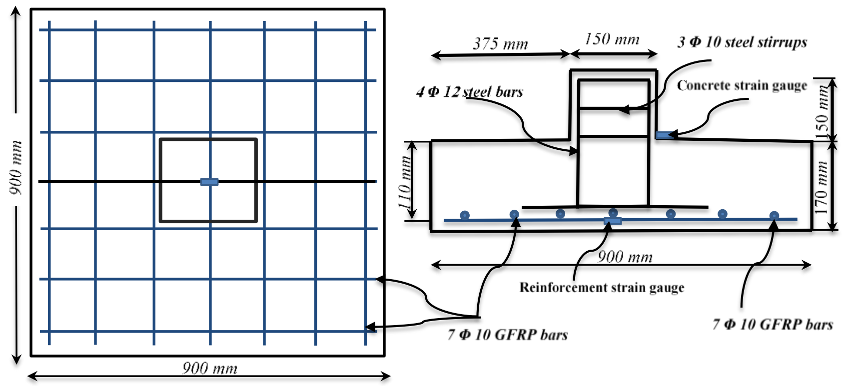
Series GF

Series (GF) included two footings (GF1 and GF2) that were reinforced with GFRP bars. They have a footprint of 900 mm x 900 mm and reinforcement ratios of 0.5 % (7 Φ10) and 1.0 % (15 Φ10) respectively. Full details of the tested footings are given in Table 1 and Fig.1.

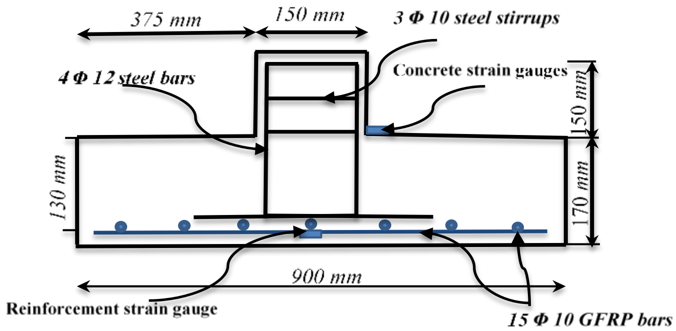
Table 1 Tested footings details

specimen	***L*** **(mm)**	***B*** **(mm)**	***h*** **(mm)**	***d*** **(mm)**	***a/d***	**reinforcement**		
						n	**Φ**	p_f **%**
Series GF								
GF1	900	900	170	130	2.88	7	10	0.5
GF2	900	900	170	130	2.88	15	10	1.0
Series SF								
SF1	900	900	170	130	2.88	7	10	0.5
SF2	900	900	170	130	2.88	15	10	1.0

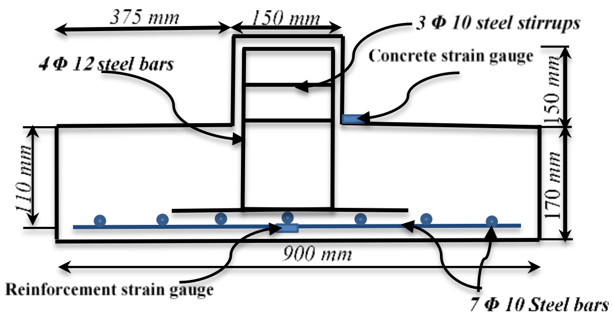
L : footing length, B: footing width, h:footing height, d:effective depth = h - concrete cover - (Φ/2), n: bars number, Φ : bars diameter and p_f : reinforcement ratio , ***a/d*** : shear span to depth ratio



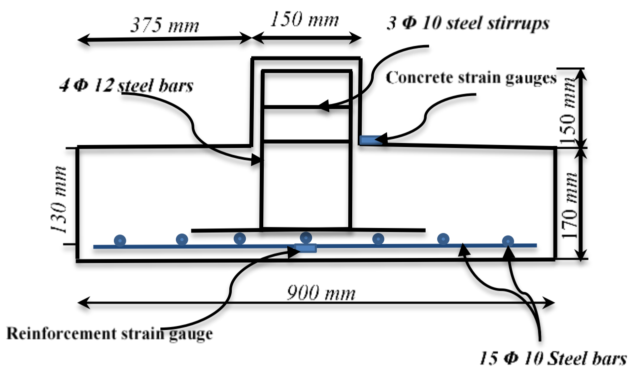
(a) Footing GF1



(b) Footing GF2



(c) Footing SF1



(d) Footing SF2

Fig. 1 Dimensions and reinforcement of the footings

Series SF

To compare the behavior of reinforced concrete footing reinforced with GFRP bars with which reinforced with steel bars, the second test series (Series SF) included two footings (SF1 and SF2) that were reinforced with steel bars. They have a footprint of 900 mm x 900 mm and reinforcement ratios of 0.5 % (7 Φ10) and 1.0 % (15 Φ10) respectively. Full details of the tested footings are given in Table 1 and Fig.1.

Material Properties

Reinforcement Bars

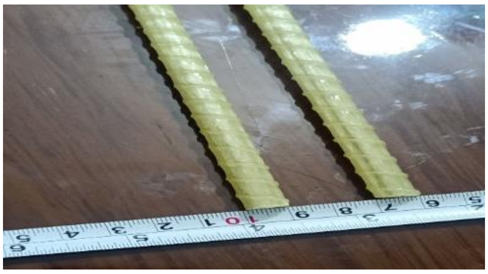
- **GFRP Bars**

Ribbed bars of Glass Fiber Reinforced Polymers (GFRP bars) with 10 mm diameters manufactured by Fiber Reinforcement Industries Co. (Fri), with 80% of glass Fibers content in volume, were used as main reinforcement in the tested concrete specimens (GF1 and CF2) For obtaining the tensile strength, and ultimate strain, etc., of the bars, five specimens of used GFRP bars were tested following ASTM D7205 [11]/ D7205M-06 [12] with a total length of 1000 mm. The length of the specimens chosen to be the sum of free length plus two times the anchor length. The length of free length equals 400 mm (40 times the diameter of the FRP bar ≥ 100 mm), and the lengths of the anchoring sections equal 300 mm (two steel tubes of 300 mm length and 4.8 mm thickness) Fig.2 The test results are shown in **خطأ! لم يتم العثور على مصدر المرجع.**.

Table 2 Test results of the bars

Properties	Sample No.				
	1	2	3	4	5
Nominal Diameter (mm)	10	10	10	10	10
Nominal Area (mm^2)	78.57	78.57	78.57	78.57	78.57
Mass Per Meter Run (gm/m)	138.0				
Ultimate Load (kN)	85.5	77.84	80.72	83.46	78.27
Ultimate Tensile Strength (Mpa)	1088.2	991.09	1027.36	1062.24	996.18
Max. Strain	0.0253	0.0230	0.0239	0.0247	0.0231

(a) GFRP tensile Strength method machine



(b) Used GFRP bars with a diameter of 10

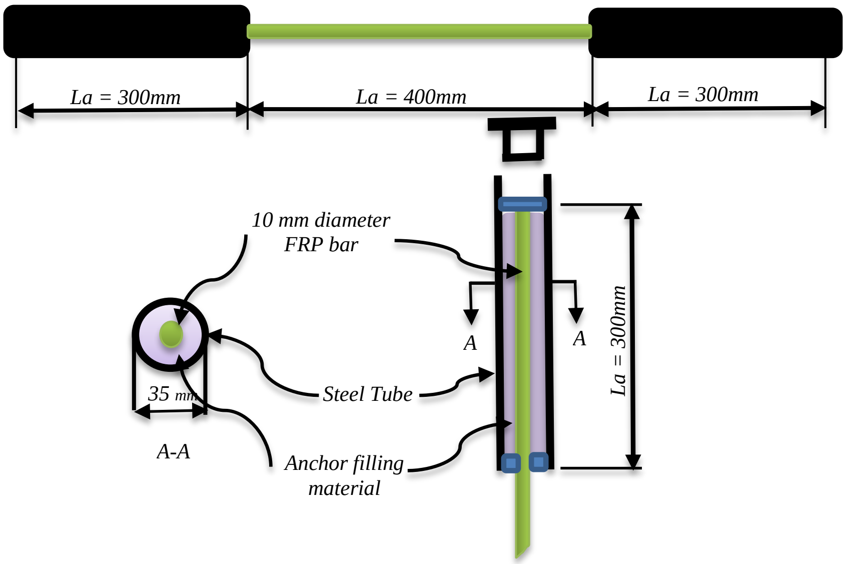


Fig. 2 Tensile properties method sample for used GFRP bars with a diameter of 10 mm

- Steel Bars

Ribbed bars of high strength steel manufactured by Egyptian Steel Company grade 400/600, with 10 mm diameters and with a nominal yield strength of 400 MPa and a modulus of elasticity of 200 GPa, were used as main reinforcement in the tested concrete specimens (SF1 and SF2) and as a transverse reinforcement for column stubs for all specimens. Ribbed bars of high strength steel grade 400/600, with 12 mm diameters and with a nominal yield strength of 400 MPa and a modulus of elasticity of 200 GPa, were used as a longitudinal reinforcement of columns stubs for all specimens.

Concrete

Medium strength concrete with a target compressive strength of 30 MPa at 28 days using crushed dolomite aggregate with a maximum size of 20 mm and ordinary Portland cement CEM I A 52.5 N manufactured by Sinai cement company were used in all footings. Table 3 summarizes the proportions of ingredients used for the concrete mix.

Table 3 concrete mix proportions of ingredients

Ingredients	Quantity (kg/m^3)
Ordinary Portland Cement (CEM I A 52.5 N)	360
Coarse Aggregate	1260
fine Aggregate	640
w/c = 0.62	

Fine Aggregate (Sand)

Fine aggregates used in this study are natural, clean, and round sand. The sand was washed and dried in an open area before used.

Coarse Aggregate (Crushed Dolomite)

Clean crushed natural Dolomite was used in the mixture as a coarse aggregate with two sizes of (10 and 20) mm. The coarse aggregate was washed using potable water to remove dust or impurities that might exist.

Mixing Process, Placing, and Curing

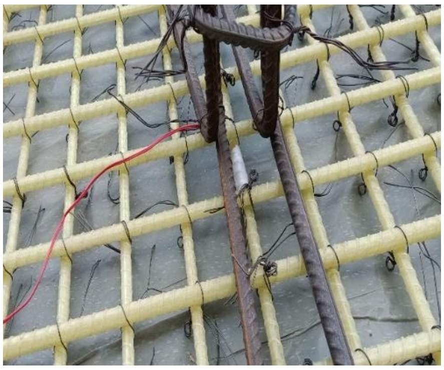
For the mixture used in this study, the cement and sand had first to be dry-mixed for 30 seconds, and then the coarse dry aggregate was added and mixed with the cement and sand for one minute until a uniform color. Water was then added slowly. The mixing process was continued for approximately 4 minutes after the addition of water. The concrete was poured from the mixer after finishing mixing directly into the formwork. An electrical vibrator was used to remove any air voids. Vibrating the concrete was processed slowly, especially around the strain gauges. From the concrete prepared in the laboratory for all specimens, six standard cubes 150 mm × 150 mm × 150 mm were prepared. the next day of casting, the cubes were removed and placed inside a curing tank. All six cubes and footings were tested after 43 days of the casting date. Table 4 summarizes the compressive strength of the prepared cubes specimens.

Table 4 Concrete tests results

Cube	*Load (KN)*	*F_{cu} (Mpa)*
C_1	715	31.8
C_2	637	28.3
C_3	752	33.4
C_4	766	34.0
C_5	646	28.7
C_6	805	35.8
Average	720.2	32.0

Test setup and instruments

For each specimen, three vertical displacements at the center of one face of the column stub and the slab corners were measured using three linear variable differential transformers (LVDT's) gauges. For the flexural reinforcement, one electrical strain gauge was attached to the intermediate reinforcing bar with a length of 10 mm and 119.6$\Omega \pm$ 0.4% gage resistance at the center of the bar below the column center for measuring the maximum reinforcement strain for all footing specimens as shown in Fig 3(a). For all footings, one concrete strain gauge with a length of 67 mm and 119.8$\Omega \pm$ 0.2% gage resistance were glued to the concrete surface at the compression side of the footing near the column face to measure the maximum concrete strains as shown in Fig 3 (b).



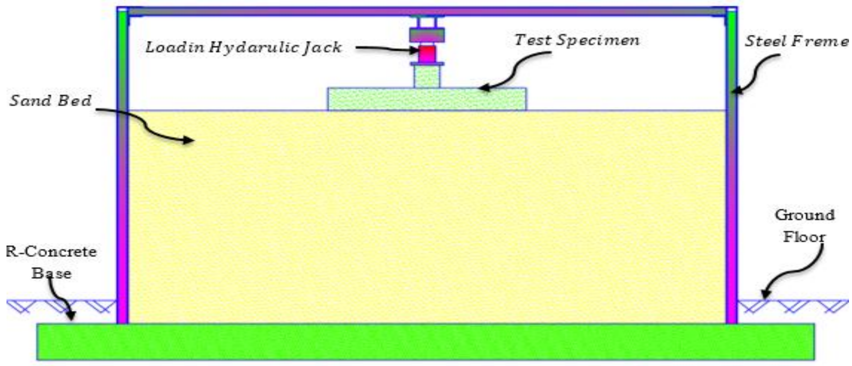
(a) Reinforcement electrical strain gauge location

(b) Linear Variable Differential Transformers (LVDT's) Gauges positions

Fig. 3 strain gauges and LVDTs locations

Test Frame

Fig.4 (a) shows the schematic representation of the test setup Frame. The test frame consists of 4 steel columns (260×260 mm in cross-section) made from two steel channels for each column connected face to face with steel plates, four edges I-beams connected with the columns by two angels at each end of them. The loading bridge consists of two I-beams connected with steel plates, which were located at the middle of two main edges bridges. The steel loading column was located in the middle of the loading bridge. All four columns were connected with a reinforced concrete ground base. To present the effect of Soil-structure interaction, all footings were realistically supported on a soil bed. The soil box was prepared with dimensions of 3.8 m x 3.8 m in plan and 2.3 m in depth. Well-graded sand layers, each 15 cm in thickness, are placed at the bottom of the frame, and then each of the layers is compacted by a plate compactor to the required modulus of compressibility fig. 4 (b). The compaction level is controlled for each layer by the sand cone test.



(a) Schematic representation of test setup Frame

(b) sand layers compaction
Fig. 4 testing frame

Testing procedure

The current footing specimens were tested after 43 days of the casting date. A vertical centric load was applied by a hydraulic jack with a maximum capacity of 50 kN placed between the steel loading column of the steel frame and the column stub. During the experimental testing, strains in the reinforcement of tested footings, vertical displacements, loading force, and concrete strain at the concrete surface at the compression side of the footing near the column face were measured at every second of the testing time

Experimental results

Crack patterns, failure modes, and failure loads

All of the four specimens showed similar cracking action. It was observed that flexural cracks happened earlier than the cracks of shear. At the first loading stages, the cracks happened at the footings mid-span, then at higher loading levels, it started to appear near mid-span approximately at the faces of the columns of footings in the top of footing tension side observed from the footings four edges. Footings GF1and SF1, with a reinforcement ratio of 0.5%, showed cracks deeper and wider than that of equal footings GF2 and SF2 with a reinforcement ratio of 1.0 % at the same loading stages. And also, the

GFRP reinforced footing specimens showed wider and deeper cracks than that of analogous steel-reinforced footing specimens. All footing specimens failed in two-way (punching) shear failure mode with no indications of flexural failure. A brittle failure with a sudden drop of the loaded area had happened, and no crushing of the concrete at the footing compression face at the column footing contact area was observed. The compression zone punching capacity was governed by splitting tension of concrete instead of crushing. Specimen GF-02 and SF-02 with a reinforcement ratio of 1.0 % showed a higher punching shear capacity than the analogous specimens GF-01 and SF-01, with a reinforcement ratio of 0.5 %. Where the observed load failure of specimens GF-02 and SF-02 were equals 311.489 and 463.962 kN, respectively, and the observed load failure of specimens GF-01 and SF-01 were equals 307.182 and 369.907 kN, respectively, with a reduction of 1.38 and 20.27 %.

Axial load versus settlement and deflection behavior

Fig.5 shows the relationships of the load and vertical displacements of corners and center of the footings for all the tested specimens. Fig.6 shows the relationships of the load and deflection for all the tested specimens. The vertical displacements were measured by using 3 LVDTs were located approximately at one of the column corners and two corners of the four footing corners. Structural deflections of specimens were calculated as the subtraction of the corners' average settlement from the displacement of the footing center recorded by LVDTs. Footing specimens GF-01 and SF-01, with a reinforcement ratio of 0.5%, showed a deflection larger than that of analogous footings GF-02 and SF-02 with a reinforcement ratio of 1.0 %.

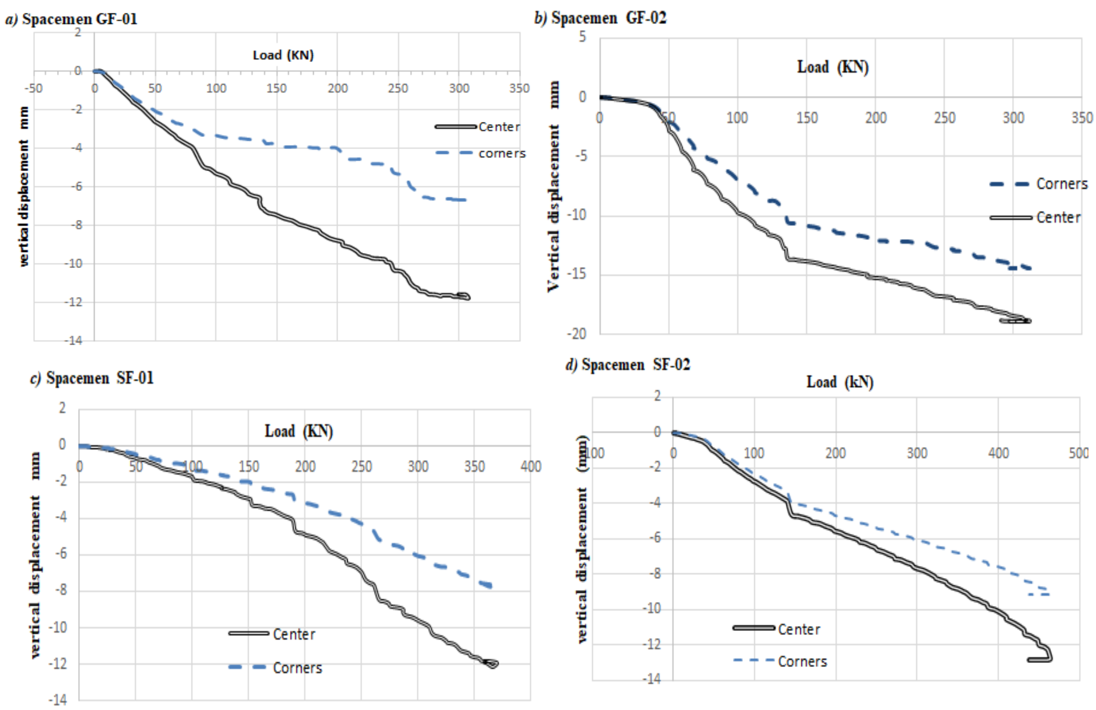


Fig. 5 The Relationship of Load and Vertical Displacement for the Tested specimens

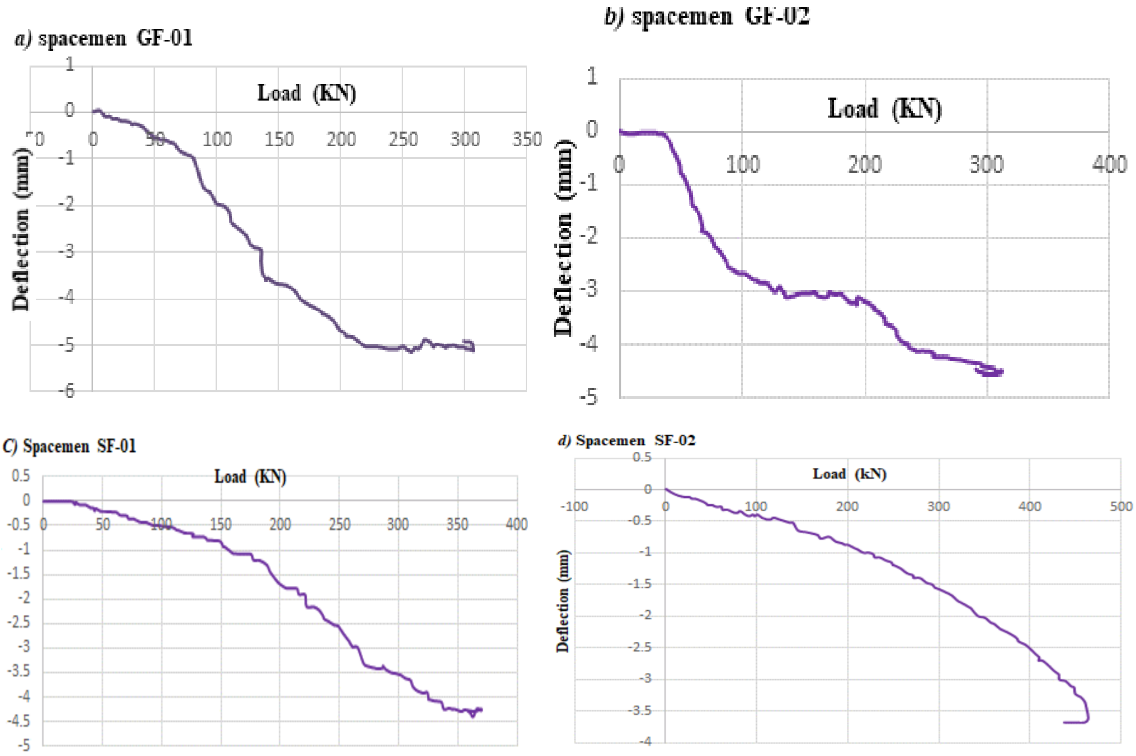


Fig. 6 The Relationship of Load and Deflection for the Tested specimens

Concrete and reinforcement strains

Fig.7 shows the relationships of the load-reinforcement strain for all the tested specimens of series GF. It was observed that the reinforcement strain gauge in specimen SF-02 malfunctioned during casting. Also it was observed that the strain gauge in specimen GF-01 malfunctioned at 44 % of failure load (135 kN). The cause of strain gauge malfunction in specimen GF-01 may be that the bar strain value exceeded the allowable strain of the strain gauge. In general, the strains of the reinforcement bars, which were measured by using one strain gauge for each footing located at the center of the bar below the column center, varied approximately linear relationship with the load increasing after cracking for all footing specimens.

Furthermore, it was observed that at service loads (P_{code}/2.1 [2]), the reinforcement strain of specimen GF-02 with a reinforcement ratio of 1.0 % was smaller than those of the analogous specimen GF-01 with a reinforcement ratio of 0.5 %. Where the reinforcement strain of specimen GF-01 at service loads represent a ratio of 21 % of the reinforcement strain of specimen GF-02 at the same load. Also, the reinforcement strain of specimen GF-01, which was reinforced with GFRP bars were larger than those of the analogous specimen SF-01, which reinforced with steel bars by 13 times at the at service load. Fig.8 shows the relationships of the load and concrete strain for all the tested specimens.

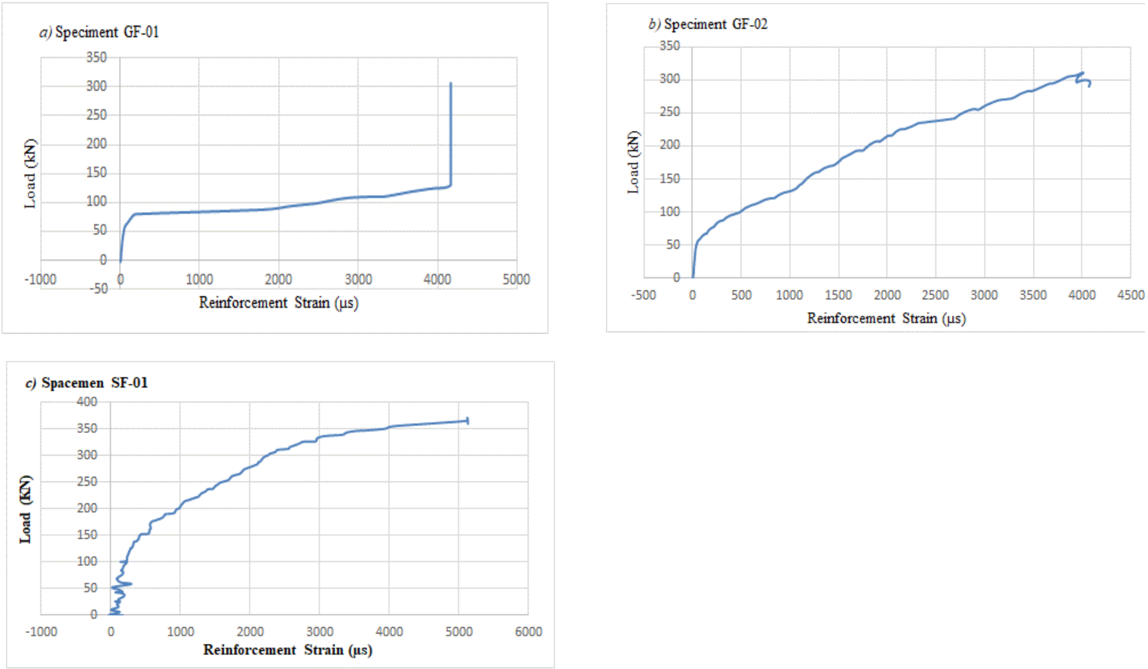


Fig. 7 The Relationship of Load and Reinforcement Strain for the tested specimens

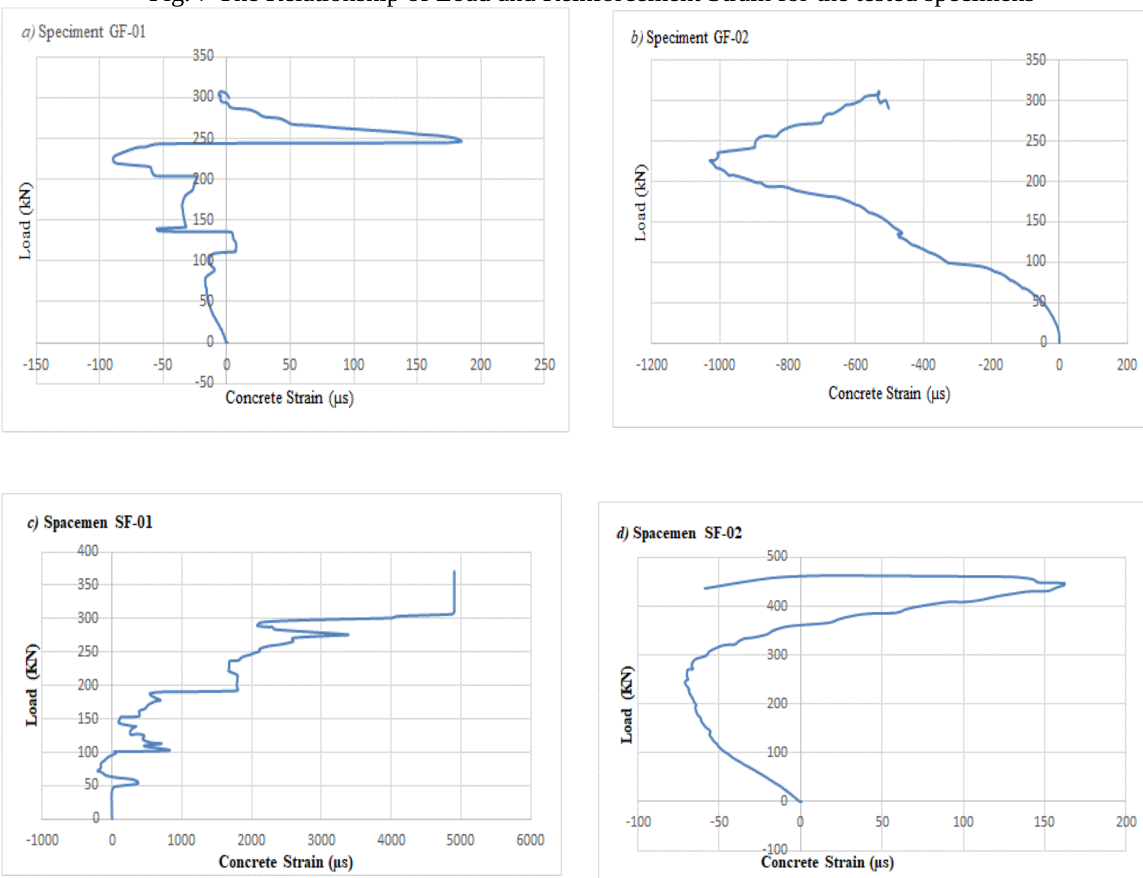


Fig.8 The relationship of Load and Concrete Strain for the Tested Specimens

Influence parameters

The effect of flexural reinforcement type (steel or GFRP)

As shown in Fig.7, footing specimens reinforced with steel bars in series (SF) show a smaller reinforcement strain than those reinforced with GFRP bars series (GF) because of the relatively smaller modulus of GFRP composite material elasticity. That cause created deeper and wider cracks in footings reinforced with GFRP bars than those of steel-reinforced footings. Deeper cracks reduce the shear strength from the uncracked concrete because of the lower depth of concrete in compression. Wider cracks, in turn, will decline the aggregate interlock contributions and residual tensile strength. Due to the small transverse strength of FRP bars and wider cracks, dowel action's contribution can be very small compared with that of steel. Finally, FRP R.C footings' overall shear capacity is smaller than that of concrete elements reinforced with steel reinforcement bars [13].

The effect of flexural reinforcement ratio.

As presented above, dowel action is one of the ways of shear transmission. If the longitudinal reinforcement GFRP or steel ratio increases, the shear capacity of R.C member increases because of the longitudinal reinforcement increasing, reduce the footing deflection, and reduce the depth of the crack and wide. Moreover, increasing the longitudinal reinforcement of GFRP bars ratio from 0.5 % in footing specimen GF-01 to 1.0% in footing specimen GF-02 increased the punching shear capacity by 1.38%. Moreover, with increasing the longitudinal reinforcement of steel bars ratio from 0.5 % in footing specimen SF-01 to 1.0% in footing specimen SF-02 increased, the punching shear capacity by 20.27 %.

Conclusions

This paper presents an experimental study for a total of 4 reinforced concrete isolated footings reinforced with GFRP and steel bars to investigate the behavior of isolated footings reinforced with GFRP bars and to compare the results with those reinforced with steel bars. Based on the obtained results from the experimental tests the following conclusions can be presented:

(1) All the tested specimens failed in two-way (punching) shear failure mode with no flexural failure indications. A brittle failure with a sudden drop of the loaded area had happened, and no crushing of the concrete at the footing compression face at the column footing contact area was observed. The compression zone punching capacity was governed by splitting tension of concrete instead of crushing.

(2) The GFRP R.C footings showed wider cracks and larger structural deflection than those similar specimens reinforced with conventional steel bars.

(3) The ultimate capacity of punching shear for footing specimens reinforced with GFRP bars was slightly similar to the ultimate capacity of punching shear for footing specimens reinforced with steel bars with a reduction of 6.47 % for footing specimens with a longitudinal reinforcement ratio of 0.5 % and with a reduction of 32.86 % for footing specimens with a longitudinal reinforcement ratio of 1.0 %.

(4) When the GFRP bars reinforcement ratio increased from 0.5 % in footing specimen GF-01 to 1.0% in footing specimen GF-02, the punching shear capacity increased by 1.38%.
(5) When the steel bars reinforcement ratio increased from 0.5 % in footing specimen SF-01 to 1.0% in footing specimen SF-02, the punching shear capacity increased by 20.27 %.

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