

Behavior of Lightweight One-Way R.C Solid Slabs Containing Hybrid Fibers– Parametric study

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Abstract: This paper investigates experimentally and numerically the flexural behavior of structural lightweight foamed reinforced concrete (LWFRC) one-way slabs reinforced with GFRP bars. Using the experimental data and compressive strength of cubes for six concrete mixes for light weight concrete with different parameters for hybrid fibers were performed. Also, one solid slab 1300 mm in length, 500 mm in width, and 100 mm in depth will be tested experimentally under two-point loads, and concrete cubes were formed after adding a hybrid fiber of polypropylene and steel fiber to determine the concrete compressive strength and use it in ANSYS software as a variable in the f_{cu} values. A verification study was conducted to validate the FEM results of single tested slab. For the parametric studies, thirteen numerical slab models were analysed using ANSYS 15 finite element modelling. The studied parameters are (1) the effect of reinforcement type, (2) the effect of reinforcement bar diameter, (3) the effect of elastic modulus of GFRP bars, (4) the effect of concrete compressive strength resulting from fiber content, fiber aspect ratio, and the volume ratio of polypropylene to steel fiber, and (5) the effect of the yield strength of steel bars. Verification of numerical models has been done by comparing the results of the load deflection curves, cracks and ultimate loads with the experimental ones. RC solid slabs were analysed and designed using ECP 203-2020 [1] under two points of loads operating at two-thirds of the span. The experimental results and the results of the ANSYS 15 nonlinear finite element program agreed well. The results also showed that the ultimate load capacity increased by 33.11% with larger GFRP bars, by 46.56% with 0.2% hybrid fibers, by 24.49% with a lower fiber aspect ratio, by 65.99% with a 1:2 PP fiber to steel ratio, and by 33.09% with an increased steel yield strength. In contrast, the ultimate load capacity decreased by 12.62% with GFRP bars compared to steel bars, and by up to 48.27% when the GFRP elastic modulus was reduced.

Keywords: Lightweight reinforced concrete; one-way solid slabs; hybrid fibers; glass fiber polymers (GFRP); numerical ANSYS 15

INTRODUCTION

Among the many benefits of using lightweight concrete as a building material are its decreased weight (less than 1800 kg/m³), enhanced durability, and suitability for longer spans [2–4]. Lightweight foamed concrete (LWC), with a density of 300–1850 kg/m³, is widely used due to its lower density compared to normal concrete. In addition to facilitating quicker construction, it provides advantages including sound and heat insulation [5–11]. Mydin et al. [12] studied the performance of lightweight foamed

concrete (LWF) with a protein-based foaming agent and partial cement replacements of GGBS, FA, RHA, and POFA at different percentages (0–60%). Experimental results showed that adding 40% GGBS, 30% FA, 20% RHA, and 30% POFA increased tensile strength but decreased slump, porosity, water absorption, bulk density, and thermal conductivity. Maglad et al. [13] studied the bending performance of steel-reinforced foamed concrete one-way slabs using structural foamed concrete with a dry density of 1600 kg/m³ and 25 MPa compressive strength.

The results showed that adding polypropylene fibers improved mechanical performance and validated the foamed concrete's structural appropriateness. The ideal fiber content (0.3%) decreased deflection by 16.46% and enhanced final load capacity by 9.7%. In order to improve the performance of lightweight foamed concrete, hybrid fibers made of steel and polypropylene (PPF) were introduced. In addition to improving fracture resistance, PPF, a robust, lightweight, and corrosion-resistant polymer, may also optimise the distribution of pore sizes in the concrete [14–17]. Steel fibers improve the tensile and flexural strength of lightweight foamed concrete, boost structural capacity, reduce crack formation and width, and improve toughness. By lowering the weight of the concrete, steel fibers provide an affordable option [18–21]. Bhat et al. [22] studied the impact of steel and polypropylene fibers on concrete's mechanical strength, fracture behavior, permeability, and spalling at room and higher temperatures. Polypropylene fibers improved impact and mechanical resistance, particularly spalling resistance. Steel fibers postponed spalling and enhanced mechanical qualities, but decreased compressive strength. Steel fiber concrete outperformed ordinary concrete by 40% between 20°C and 700°C. Hakeem et al. [23] studied the impact of steel fibers on bubble slabs, comparing five slabs with varying fiber content. According to the results, the addition of steel fibers greatly enhanced structural performance by raising yield and ultimate loads and changing the failure mode from brittle shear to ductile flexural failure. FRP may be used to strengthen structures, increasing their service life and reducing maintenance costs because it does not corrode [24–26]. GFRP bars are increasingly used in RC structures due to their high tensile strength, corrosion resistance, light weight, and ease of handling [26–28]. Adam et al. [29] investigated the structural performance of high-strength concrete slabs reinforced with locally made GFRP bars. According to the results, GFRP-reinforced slabs exhibited superior fracture patterns and more ductility and deflection than steel-reinforced ones, particularly when the reinforcement ratios were equal. The experimental results were in good agreement with the finite element model results. Li et al. [30] investigated the flexural performance of lightweight ultra-high-performance fiber-reinforced concrete beams reinforced with high-strength steel and GFRP bars under four-point bending was. The findings indicated that as reinforcement increased, GFRP-reinforced beams exhibited greater peak loads, stiffness, and cracking loads but decreased ductility. GFRP-reinforced beams exhibited greater deflection, decreased bending strength, and accelerated stiffness degradation and crack formation in contrast to steel-reinforced beams. Slab analysis,

comparison with experimental data, and simulation of actual material properties and loading techniques were all done using the ANSYS 15 nonlinear finite element program. Researchers [31–34] confirmed that the ANSYS program can properly analyse and predict nonlinear behaviour of solid slabs.

2. EXPERIMENTAL PROGRAM

2.1 The test specimens' description

The experimental program investigated the flexural behavior of structural lightweight concrete one-way solid slabs reinforced with hybrid fibers. One slab specimen was tested at Cairo University. The slab measured 1300 mm in length, 500 mm in width, and 100 mm in thickness, with an effective depth of 85 mm. It was reinforced with a bottom mesh consisting of 8 mm diameter glass fiber reinforced polymer (GFRP) bars and subjected to two-point loading applied symmetrically at one-third of the span from the center of the slab. Fig. 1 shows the specimen dimensions and reinforcement details.

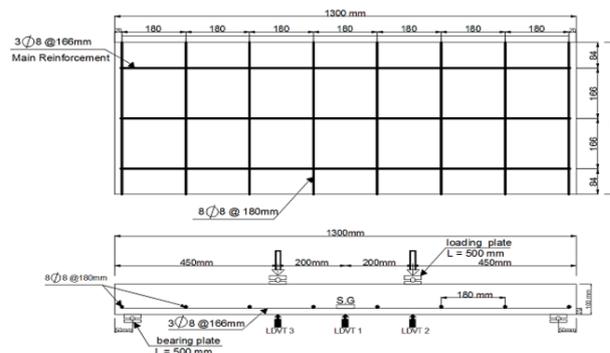


Fig 1. The test specimens' complete concrete dimensions and reinforcing information.

2.2 Materials used

Materials utilized in this experimental program for preparing lightweight concrete include dry solids such as cement (42.5N), sand, coarse aggregate, silica fume, and foam, and liquid materials such as Sika Air, superplasticizer (Sikament NN), and water. In order to get the desired compressive strength, Table 1 displays the mix percentage by weight of the components for one cubic meter of concrete. After 28 days (the testing day), the average concrete strength was 245 kg/cm². The average density for the slab was 1.9 g/cm³. The slab was reinforced using glass fiber polymer (GFRP) bars. Additional mixes were prepared and cast into cubes to determine the compressive strength values of concrete (f_{cu}) after 28 days for use in the parametric study using ANSYS 15.0 finite element analysis software. Table 2 shows the components of the additional mixes that were prepared and cast into cubes and the compressive strength values of the concrete (f_{cu}). As shown in Fig. 2, six cubes (150 × 150 × 150 mm) were cast for each mix to determine

compressive strength. Fig. 3 shows the comparison of compressive strength values (f_{cu}) for each concrete mix.

TABLE 1. Mix design proportions of lightweight concrete per one cubic meter.

Type	Cement	Sand	Coarse Aggregate	Silica Fume	Foam	Sika Air	Super-Plasticizer	Water
Weight (Kg)	500	460	635	75	21	0.75	5	203
Specific gravity(Kn/m ³)	31.5	25.9	27.2	22	0.7	10.1	11.5	10

TABLE 2. Mix variables, fiber characteristics, and corresponding f_{cu} values.

Mix No.	Fiber Content V_f % of Concrete Volume	Fiber Aspect Ratio l_f/ϕ	Volume of Polypropylene Fiber : Steel Fiber	Concrete compressive strength f_{cu} (MPa)
M1	-	-	-	24.5
M2	0.10%	50	1:1	32.9
M3	0.20%	50	1:1	35.2
M4	0.10%	25	1:1	33.4
M5	0.10%	50	2:1	26.7
M6	0.10%	50	1:2	35.6



(a) Casting lightweight concrete cubes (b) Typical concrete cubes

Fig 2. Preparing lightweight concrete cubes.

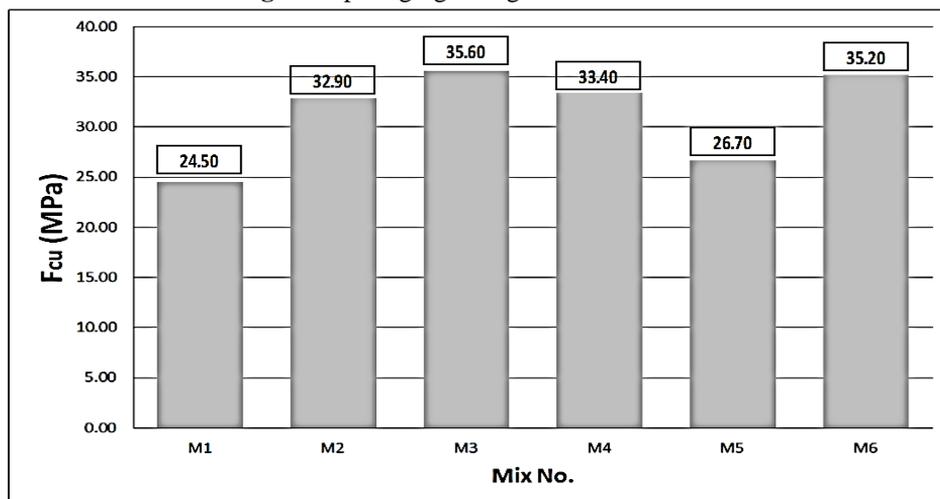


Fig 3. The comparison of compressive strength values for each concrete mix.

2.3. Experimental results

2.3.1. Crack Patterns, and Failure Mode

During testing, it was observed that the first crack loads for specimen S1 were 6.82 kN. The cracks were vertical flexural cracks that were located close to the constant moment area and the tension zone. New cracks continued to develop as the existing ones expanded vertically towards the compression zone, and little branches began to appear along the lower stress surface. The rate of new cracks then sharply declines at increasing loading levels. At this point, pre-existing cracks, particularly the older ones, become wider and deeper before slanting and following lines of compression stress. The cracks continue to widen until the slab collapses at a load of 26.95 kN. The width of the largest crack as measured by a crack lens was 7.5 mm. Fig. 4 shows the crack patterns for the specimen S1.

2.3.2. Load deflection curves

The load-deflection curve for the tested slab is shown in Fig. 5. Initially, the slab exhibited a relatively linear elastic behavior up to the cracking load, when the concrete cracked at the tension face. Beyond this point, deflection increased as the slab stiffness decreased more rapidly. This was mainly due to the low elastic modulus of the GFRP bars.



Fig 4. Experimental crack pattern of specimen S1 showing vertical flexural cracks in the tension zone at failure load.

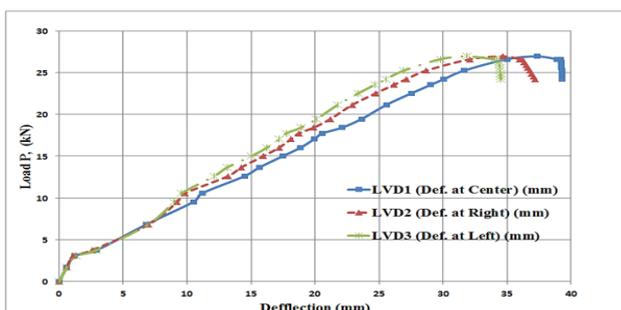


Fig 5. The load deflection curve of the specimen (S1).

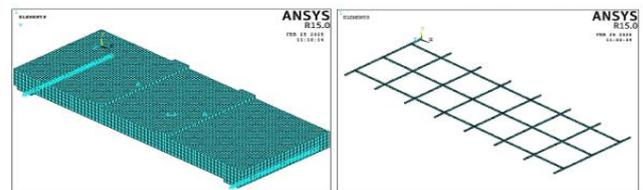
3. FINITE ELEMENT ANALYSIS

The ANSYS 15.0 program was used to model concrete slabs using SOLID65 for concrete, LINK180 for reinforcement bars, and SOLID185 for steel loading plates. Nonlinear material properties were assigned, and flexural stresses, deflections, and crack failure patterns were analysed at key slab locations. Flexural strain

variations at the slab centers were also recorded. The slabs were designed according to the 2020 Egyptian Code [1].

3.1. Finite Element Model of Slabs

This study simulated thirteen reinforced concrete slabs using ANSYS V.15 with a mesh size of $10 \times 10 \times 20$ mm, incorporating various flexural characteristics. The dimensions of each studied reinforced concrete slab are $1300 \times 500 \times 100$ mm, as shown in Fig. 6, and also show the steel reinforcement for the models. Assuming perfect bonding of the reinforcement to concrete, the study used LINK180 components to represent bottom longitudinal reinforcement using the embedded element approach. This technique enabled direct load transfer, eliminated bond-slip effects, and provided a reliable approximation of structural behavior, although bond deterioration at high stress was not considered.



(a) Concrete elements (b) Reinforcing bar elements

Fig 6. Typical slabs of reinforced concrete elements.

3.2. Numerical results and verification studies

One specimen was experimentally tested and modelled using ANSYS 15. The accuracy of the numerical simulation was confirmed by comparing the ANSYS 15 results with the experimental findings. Additionally, new slab variables on ANSYS 15 were investigated. Fig. 7 presents the crack pattern of numerical results for specimen S1. As shown in Fig. 8, the load-deflection curves from both the experimental and numerical analyses for specimen S1 are also compared. The finite element load-deflection curves closely matched the experimental results, showing high modelling accuracy. The results demonstrated a strong agreement between experimental and numerical findings. Table 3 summarises the comparison of the experimental and numerical results. Fig. 9 shows the deformed shape and deflection of specimen S1. According to the comparison in Table 3, the first cracking load was 6.82 kN experimentally and 6.61 kN numerically, giving a close ratio of 1.03. The corresponding cracking deflections were 6.79 mm and 6.42 mm, with a ratio of 1.06. For the ultimate load, the experimental value was 26.95 kN compared to 30.99 kN from the numerical analysis, resulting in a ratio of 0.87. The ultimate deflection was 37.32 mm experimentally versus 40.59 mm numerically, with a ratio of 0.92. These results confirm that ANSYS provided reliable predictions, with only slight overestimation of the ultimate capacity and deflection.

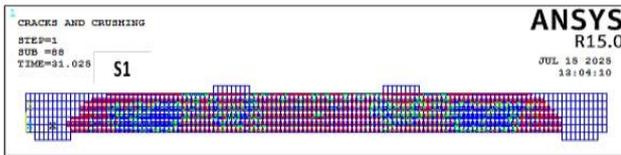


Fig 7. Numerical crack pattern of specimen S1 obtained from ANSYS analysis

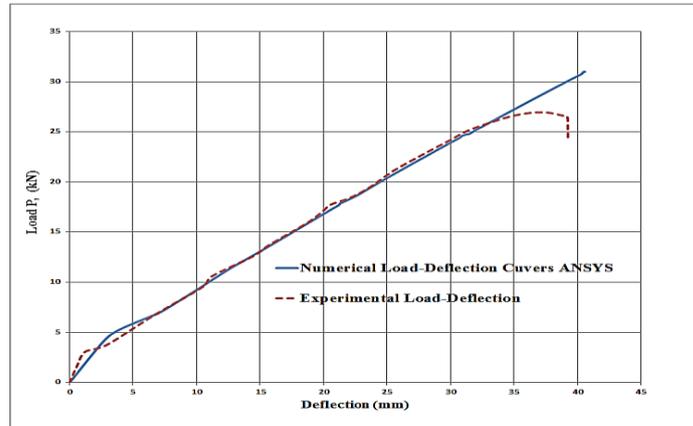
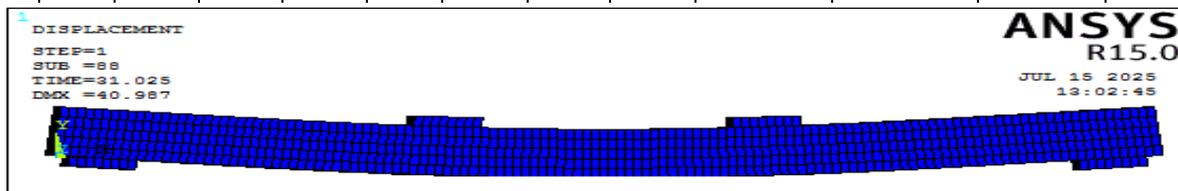


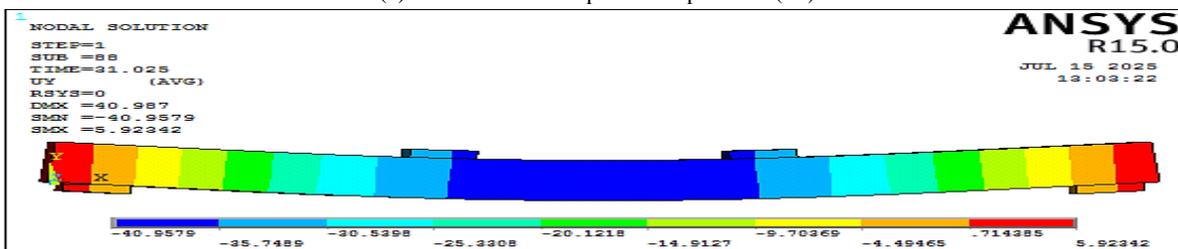
Fig 8. Load deflection curve for experimental and numerical for specimen S1.

TABLE 3. Comparison of the experimental and numerical results.

Slab No.	Experimental Results				Numerical Results				Experimental Results/Numerical Results			
	P_{cr} (kN)	Δ_{cr} (mm)	P_u (kN)	Δ_u (mm)	P_{cr} (kN)	Δ_{cr} (mm)	P_u (kN)	Δ_u (mm)	$\frac{P_{cr} - exp}{P_{cr} - NL}$	$\frac{\Delta_{cr} - exp}{\Delta_{cr} - NL}$	$\frac{P_u - exp}{P_u - NL}$	$\frac{\Delta_u - exp}{\Delta_u - NL}$
	S1	6.82	6.79	26.95	37.32	6.61	6.42	30.99	40.59	1.03	1.06	0.87



(a) The deformed shape of the specimen (S1)



(b) The deflection of the specimen (S1)

Fig 9. Numerical deformed shape and deflection of specimen (S1).

TABLE 4. The studied parameters and numerical results.

Slab No.	Studied Parameters					Numerical Results	
	Material	Bars	F_{cu} (MPa)	E_{GFRP}	F_y (MPa)	P_u (kN)	δ_u (mm)
S1	GFRP	3 ϕ 8	24.5	50000	-	30.99	40.59
S2	GFRP	3 ϕ 10	24.5	50000	-	37.91	34.36
S3	GFRP	3 ϕ 12	24.5	50000	-	41.25	32.48
S4	Steel	3 ϕ 8	24.5	-	240	27.08	36.02
S5	GFRP	3 ϕ 8	24.5	40000	-	21.65	33.08
S6	GFRP	3 ϕ 8	24.5	30000	-	16.03	30.64
S7	GFRP	3 ϕ 8	32.9	50000	-	37.62	38.70
S8	GFRP	3 ϕ 8	35.2	50000	-	45.42	38.37
S9	GFRP	3 ϕ 8	33.4	50000	-	38.58	45.01
S10	GFRP	3 ϕ 8	26.7	50000	-	40.72	39.69
S11	GFRP	3 ϕ 8	35.6	50000	-	51.44	42.66
S12	Steel	3 ϕ 8	24.5	-	360	31.83	35.84
S13	Steel	3 ϕ 8	24.5	-	420	36.04	36.09

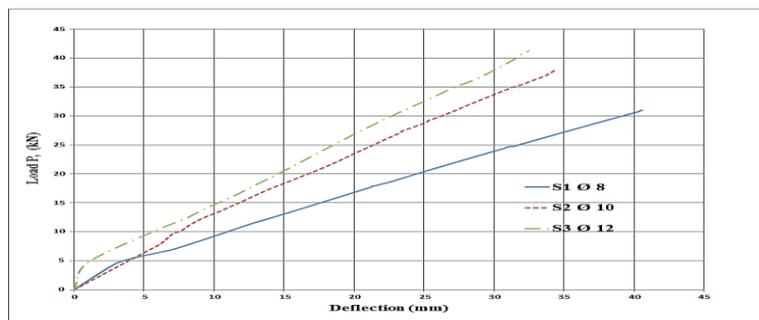


Fig 10. Parametric study for the effect of reinforcement bar diameter

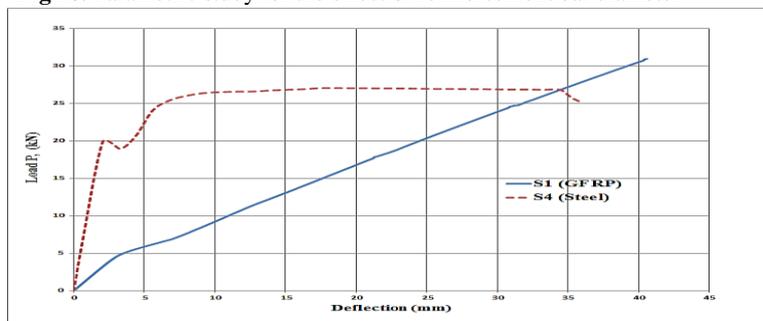


Fig 11. Parametric study for the effect of reinforcement type

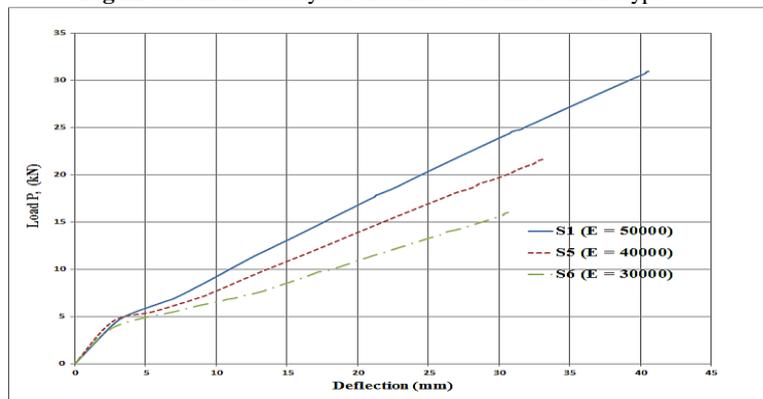


Fig 12. Parametric study for the effect of elastic modulus of GFRP bars

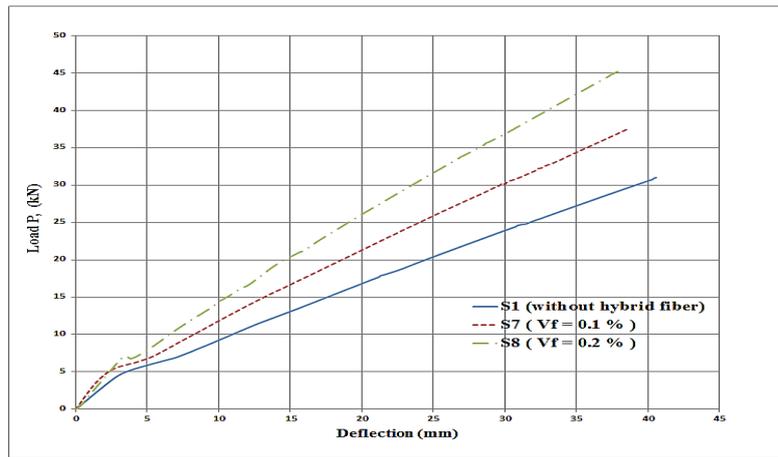


FIG 13. Parametric study for the effect of fiber content

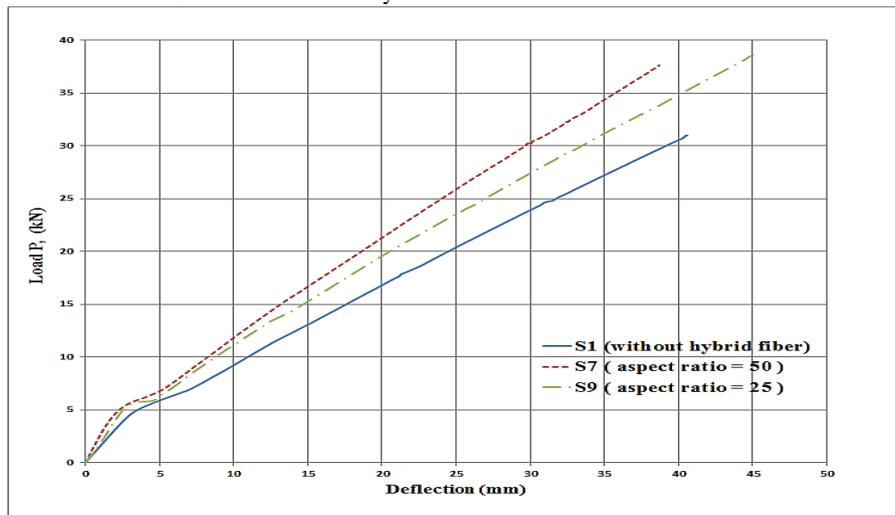


FIG 14. Parametric study for the effect of fiber aspect ratios

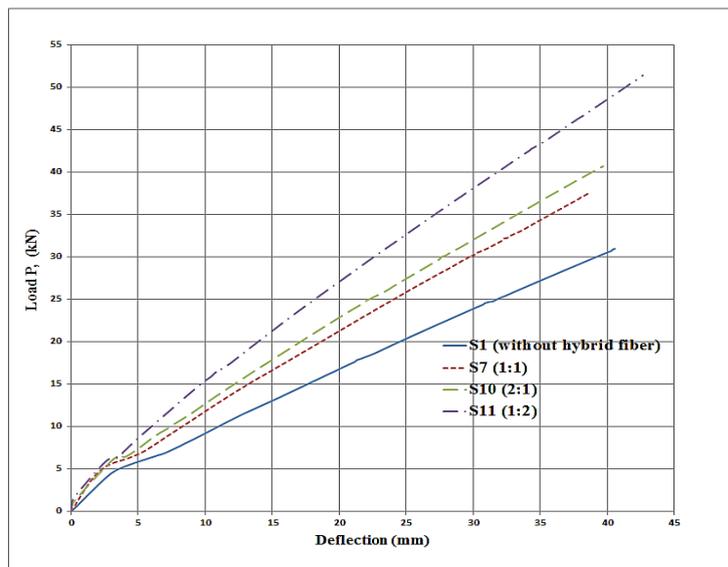


FIG 15. Parametric study for the effect of the volume ratio of polypropylene fiber to steel fiber

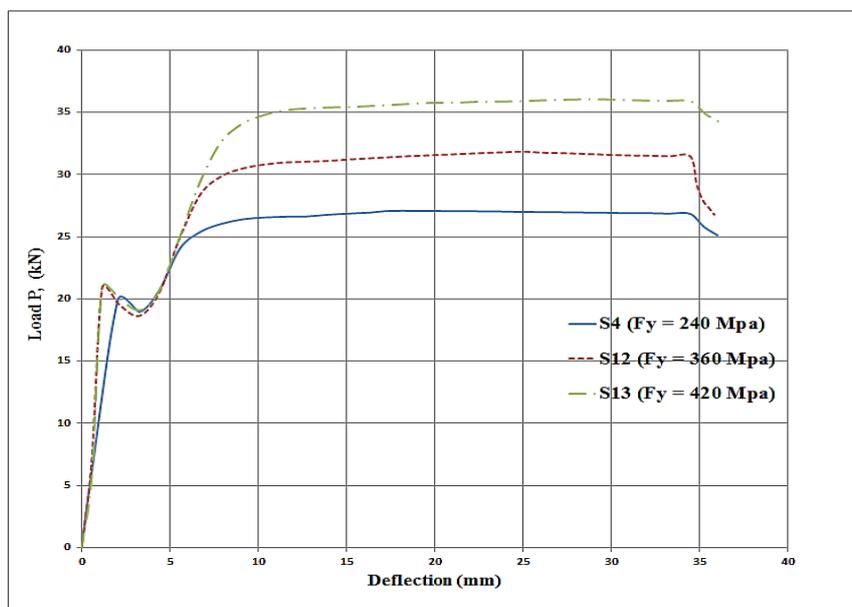


FIG 16. Parametric study for the effect of the yield strength of the steel bars

5. Conclusions

1. The results from the ANSYS 15 nonlinear finite element software matched well with the experimental data, showing 103.13% for the first crack load, 86.95% for the ultimate load, and 91.95% for the displacement at ultimate load. Flexure failure was the mode of failure for every tested (LWFRC) one-way solid slab.
2. It was noted that increasing the diameter of the GFRP reinforcement bars from 8 mm to 10 mm and then to 12 mm resulted in an increase in the ultimate load-carrying capacity by 22.33% and 33.11%, respectively, while the displacement decreased by 15.35% and 19.98%, respectively.
3. Comparing solid slabs reinforced with GFRP bars to a solid slab reinforced with conventional steel bars, the ultimate load-carrying capacity decreased by 12.62%, and the displacement dropped by 11.26%.
4. As the elastic modulus of the GFRP bars was decreased from 50000 to 40000 and subsequently to 30000, it was observed that the ultimate load-carrying capacity dropped by 30.14% and 48.27%, respectively, while the displacement decreased by 18.50% and 24.51%.
5. In comparison to a solid slab without hybrid fibers, the addition of 0.1% and 0.2% hybrid fiber content to solid slabs increased the ultimate load-carrying capacity by 21.39% and 46.56%, respectively, while the displacement dropped by 4.66% and 5.5%, respectively.
6. Reducing the fiber aspect ratio from 50 to 25 resulted in a 10.89% increase in displacement and a 24.49% improvement in ultimate load-carrying capacity compared to the solid slab without hybrid fibers.
7. When the amount of polypropylene fiber to steel fiber was 2:1, the displacement dropped by 2.22% and the final load-carrying capacity improved by 31.4%. Conversely, the ultimate load-carrying capacity and displacement rose by 65.99% and 5.1%, respectively, when the amount of polypropylene fiber to steel fiber was 1:2.
8. When using conventional steel bars in LWFRC solid slabs, increasing the yield strength of the steel bars (f_y) from 240 MPa to 420 MPa resulted in a 33.09% increase in ultimate load-carrying capacity and a 0.19% increase in displacement.

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