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Deformation Behavior of Reinforced Concrete Two-Way Slabs Strengthened with Different Widths and Configurations of GFRP

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Abstract

In this paper, we conducted a numerical analysis of the deformation behavior of Steel-reinforced concrete (RC) two-way slabs strengthened by glass fiber reinforced polymer (GFRP) with different widths and configurations. A total number of 36 RC slabs of $12 \times 300 \times 300$ cm were used in this numerical study. Also, a column of $30 \times 30\ cm$ was considered in the center of the slab for applying static loading. The bonded GFRP strips had 5, 7.5 and 10 cm width (W) and configured in three models called PM1, PM2, and DM. In PM1 (strip length = 2.4 m) and PM2 (strip length =1.7 m) configurations, the strips were bonded in two directions parallel to the sides of the slab, while in DM configuration (strip length =1.7 m), strips were rotated with 45 degree angle around the central axis that is perpendicular to the surface of the slab. According to the comparison results, we found out that the 5-cm wide strips with PM1 configuration having a parallel space of 0.5 times the strip width ($0.5W$) greatly reduced the deformation of RC two-way slab compared to other strip widths and configurations, while $10\ cm$ strips under all configurations, highly increased the deformation when space between strips varied from $1.5W$ to $2W$.

Keywords: Glass Fiber Reinforced Polymer; Reinforced Concrete Slabs; Finite Element Analysis.

1. Introduction

Since the early 1990s, the use of synthetic Fiber-Reinforced Polymers or Fiber Reinforced plastics (FRP) has become popular for strengthening and repair of reinforced concrete structures. FRP is a composite material made of a polymer matrix reinforced with fibers. FRPs are a category of composite plastics that specifically use fiber materials to mechanically enhance the strength and elasticity of plastics. “FRP offers the engineers an outstanding combination of properties such as low weight, easier site handling, immunity from corrosion, excellent mechanical strength and stiffness, and the ability of formation in long lengths, thus eliminating the need for lap joints”[1]. The fibers are usually glass, carbon, aramid, or basalt, all of which have been used in many studies with seismic recovery practical purposes (e.g. [2, 3]). Among these, glass fibers are the most widely used FRPs in the composite industry. The advantages of this type of fiber can be low cost, high tensile strength, resistance to chemical agents, and good resistance to high temperatures.

Currently, strengthening with FRPs has been applied to structures such as column, beams, walls, slabs. In flexural reinforcement of concrete slabs with FRPs, typically, the FRP strips or plates are pasted to the tensile surface of concrete slabs. This pasting can either cover part of the slab surface [4-6] or cover the whole surface of the slab [4, 6, 7]. For FRP-upgraded members, failure may occur in different modes depending on parameters such as member size, steel reinforcement ratio, FRP properties and dimensions. Sources of FRP debonding include local cracks in a host concrete

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member, degradation of FRP-concrete interface, and stress concentrations induced by FRP configurations and irregular concrete surface [8-10].

There are numerous studies on flexural strengthening of RC slabs using FRP composites. For example, Teng et al. [11] presented an experimental study of the feasibility of strengthening deficient reinforced concrete cantilever slabs by bonding glass FRP strips/sheets on the top surface (the tension side). Based on the test results, a simple and effective method was identified where the GFRP strips were anchored into the walls through horizontal slots and onto the slab using fiber anchors. Seim et al. [12] studied experimentally the effect of prefabricated FRP strips and fabric on the behavior of reinforced concrete one-way slabs. They concluded that failure is associated with a drastically reduced deformation capability and a change from the conventional ductile mode of failure to a more brittle one. Zhang et al. [13] experimentally studied the behavior and strength of two-way square reinforced concrete slabs bonded with a steel plate and showed that debonding failures are unlikely in these plated slabs. Arduini et al. [14] experimentally investigated the behavior of one-way reinforced concrete slabs strengthened with unidirectional carbon fiber-reinforced polymer and found different failure mechanisms such as concrete shear, concrete crushing, and FRP rupture. Xue et al. [15] studied four FRP-concrete composite slabs and one FRP profile without concrete slabs through two types of shear connectors including FRP perfobond shear connectors and epoxy adhesive under positive and negative loads. For composite specimens under negative loads, flexural buckling failure was observed on the top flanges of FRP profiles; while shear buckling failure occurred on the webs of FRP profiles for those under positive loads.

Most of these studies are experimental; only a limited number of studies are available based on a numerical modelling. Elsayed et al. [16] and Lesmana and Hu [17] focused on numerical modeling of the FRP-to-concrete interfacial behavior in FRP-strengthened two-way slabs. Elsanadedy et al. [10] numerically investigated reinforced concrete one-way slabs upgraded with Glass Fiber Reinforced Polymer (GFRP) composites using nonlinear Finite Element (FE) analysis in LS-DYNA software. As a result, they introduced new stiffness and reinforcement parameters. The results of a numerical study showed that the behavior of FRP- strengthened reinforced concrete members can be estimated by using numerical methods without having to carry out costing experiments [18].

In this paper, we used FE analysis in ABAQUS software to examine the effect of width and configuration of GFRP strips on FRP-strengthened reinforced concrete (RC) two-way slabs behavior to investigate the performance of these strips in strengthening RC two-way slabs. We assumed that (1) There was bonding between GPRP strips and the RC slabs during the loading; (2) Concrete had nonlinear behavior; and (3) GFRP strips may be rupture under pressure loading. Our purpose is to find the optimum width, space and configuration of GFRP strips to reduce deformation and increase the load of RC slabs.

2. Research Methodology

2.1. Specimens Details and Reinforcement Modelling

A total number 36 strengthened RC two-way slabs of $12 \times 300 \times 300\ cm$ (test specimens) were used in this study. Studied slabs had compressive strength of 25 MPa and elastic modulus of $23500\ MPa$ with a Poisson's ratio of 0.2. The concrete was made to class C25. A column of $30 \times 30\ cm$ was considered in the center of the slab for applying static loading (Figure 1a). To simplify the problem and increase the speed of numerical analysis, by removing the geometry of the column, the force applied from the column to the slab was replaced by the equivalent pressure load, applied to the slab at a surface equal to the column's dimensions (Figure 2b). Also, to apply boundary conditions, the modeled slabs were placed in all four sides of the lower side with a distance of 10 cm from the edge in three directions (X, Y, and Z). For the reinforcement of the analyzed concrete slabs, steel rebar's with a diameter of $10\ mm$ and a length of $290\ cm$ were located in two directions at a distance of $30\ cm$ from each other. These bars were located in the tensile surface of the slab, covering 4 cm from the bottom and 5 cm from the side faces. Rebar's' yield stress was $350\ MPa$, with an elastic modulus of $210\ GPa$, Poisson's ratio of 0.3, yield strain of 0.002, and ultimate strain of 0.12. Bilinear elastic-plastic model was used to model the behavior of steel, and Two-node linear 3D truss element (T3D2) was employed to model the reinforcement steel (see Figure 2). In order to define the interaction between concrete and steel bars, the bars were embedded in concrete; therefore, the slip effects between the concrete and reinforcement were ignored.

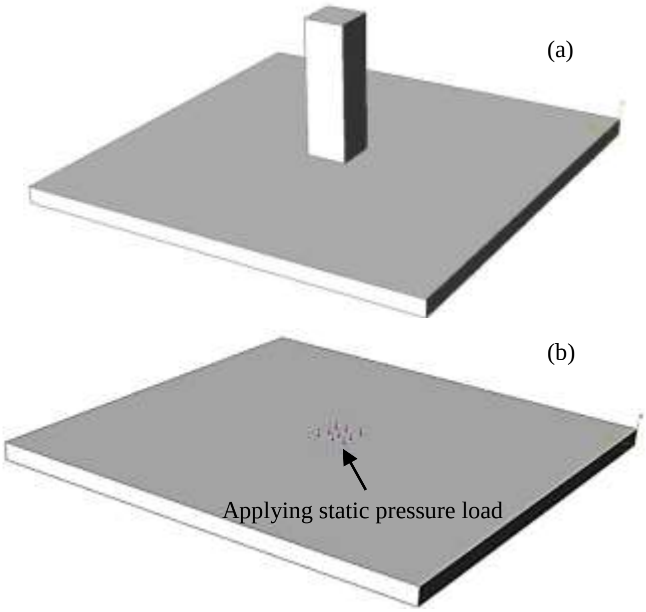


Figure 1. Using a column (a) for applying the static load to the concrete slab equal to column dimensions (b)

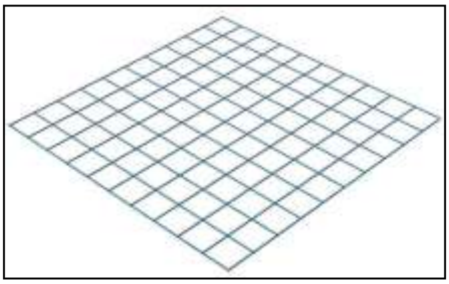


Figure 2. Model of the reinforcement steel

2.2. FRP Modelling

To investigate the role of FRP composites in concrete slab reinforcement, the strips with only longitudinal fibers were used. Studied polymer strips were three glass fibers with 5, 7.5 and 10 cm width (W). Table 1 presents mechanical properties of these strips. They were positioned from each other as 0.5, 1, 1.5 and 2 times the width of the strips. The resin was applied to the concrete and then strips were bonded to the tensile surface of concrete two-way slabs in accordance with the manufacturer's instructions, and configured as shown in Figure 3. Configurations were named as PM1, PM2, and DM. In PM1 and PM2 configurations, GFRP strips were bonded in two directions parallel to the sides of the slab, while in DM model, they were rotated with 45 degree angle around the central axis that is perpendicular to the surface of the slab. Strip length in PM1 was 2.4 m and in DM and PM2 configurations, it was 1.7 m. In PM1 and DM models, the strips extended up to a distance of 20 cm from the supports (30 cm from the edge of the slab). Overall, 36 configurations were considered for the study with different specifications shown in Table 2.

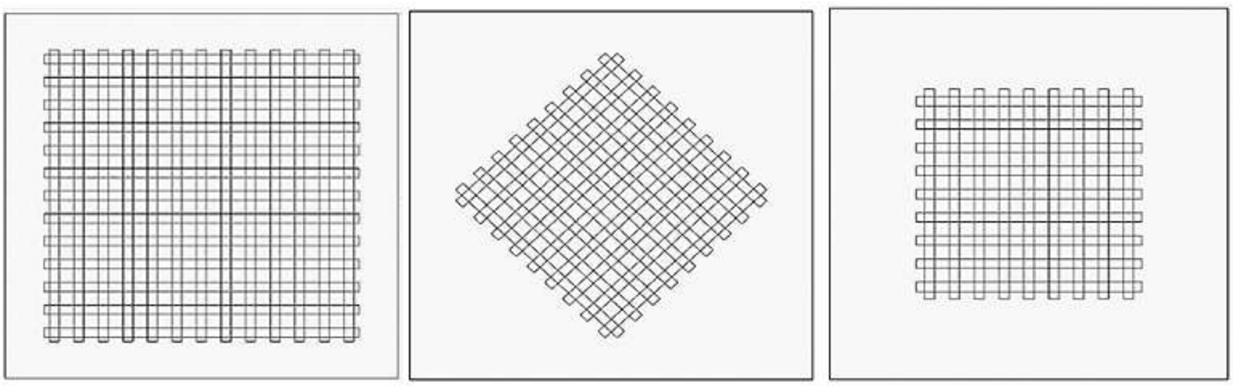


Figure 3. Three configurations of GFRP strips bonded to RC slabs: Left: PM1, Center: DM, Right: PM2

Table 1. Mechanical properties of GFRP strips

Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)	Rupture resistance (MPa)	Thickness (mm)
$E_x = 55$		$G_{xy} = 2.7$		
$E_y = 4.1$	0.26	$G_{yz} = 1.55$	3500	1
$E_z = 4.1$		$G_{zx} = 2.7$		

Table 2. Number and spaces of GFRP strips in each configuration

Width of strips (cm)	Space between strips (× width of strips)	Configurations			
		PM1 (length= 2.4 m)		PM2 and DM (length= 1.7 m)	
		Strip Number	Area (m^2)	Strip Number	Area (m^2)
5	0.5W = 2.5 cm	64	7.68	46	3.91
	1W = 5 cm	48	5.76	34	2.89
	1.5W = 7.5 cm	38	4.56	28	2.38
	2W = 10 cm	32	3.84	24	2.04
7.5	0.5W = 3.7 cm	42	7.56	30	3.83
	1W = 7.5 cm	32	5.76	22	2.81
	1.5W = 11.2 cm	26	4.68	18	2.3
	2W = 15 cm	21	3.78	16	2.04
10	0.5W = 5 cm	32	7.68	22	3.74
	1W = 10 cm	24	5.76	18	3.06
	1.5W = 15 cm	20	4.8	14	2.38
	2W = 20 cm	16	3.84	12	2.04

2.3. Meshing

For generating the FRP model coupled with reinforced concrete model in software, we used 8-node structural finite element which is presented in Figure 4.

Figure 4. Three-dimensional model of FRP strips coupled with RC slab

2.4. Concrete Behavior Modeling

Concrete damage plasticity (CDP) model was used to describe the concrete in the models. It assumes two main failure mechanisms: the tensile cracking and the compressive crushing. The evolution of the yield surface is controlled by tensile and compressive equivalent plastic strains. In CDP model, ψ is the dilation angle; E is an eccentricity of the plastic potential surface with default value of 0.1; the ratio of initial biaxial compressive yield stress to initial uniaxial compressive yield stress (σ_{b0}/σ_{c0}) with default value of 1.16; and K_c is the ratio of the second stress invariant on the tensile meridian to compressive meridian at initial yield [19]. Figure 5. shows behaviour of concrete under axial compressive and tension strength.

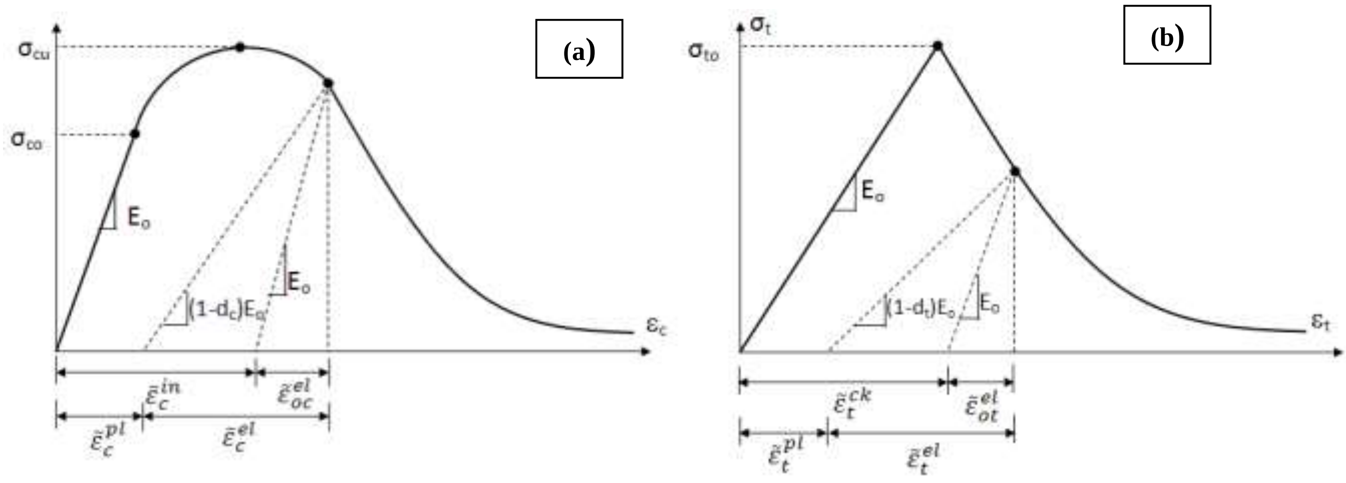


Figure 5. Behavior of concrete under axial compressive (a) and tension (b) strength [19]

In this study for presenting stress-strain behavior of concrete under uniaxial compression we used Hognestad [20]'s modified formulation (Equation 1).

$$f_c = f_c''\left[\frac{2\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right]$$
$$f_c'' = k_s . f_c' \qquad (1)$$
$$\varepsilon_0 = 1.8\frac{f_c''}{E_c}$$

Where f_c is the concrete compressive strength, f" is the maximum compression in the concrete member, f_c' is uniaxial 28-day compressive strength, ε_c is compressive strain, ε_0 is the strain at the maximum concrete stress, and E_c is the modulus of elasticity of normal-weight concrete. For concretes with a cylindrical compressive strength of 15, 20, 25, 30 and equal to greater than 35 MPa, k_s is considered to be 1, 0.97, 0.95, 0.93, and 0.92, respectively. The modified Hognestad curve consists of a second-degree parabola up to a strain of $18f_c'/E_c$, where $f_c'' = 0.9\ f'_c$, followed by a linear descending branch with a limiting strain of 0.0038. The stress-strain curve of concrete is introduced by assigning inelastic strains to their corresponding stresses according to Equation 2. [19], where ε_{in} represents inelastic strain, ε_{el} is elastic strain, ε_t is tensile strain, and σ_t is tensile stress.

$$\varepsilon_{in} = \varepsilon_t - \varepsilon_{el}$$
$$\varepsilon_{el} = \frac{\sigma_t}{E} \qquad (2)$$

In order to show stress-strain behavior of concrete under uniaxial tension we employed the relations which are shown in Figure 6.

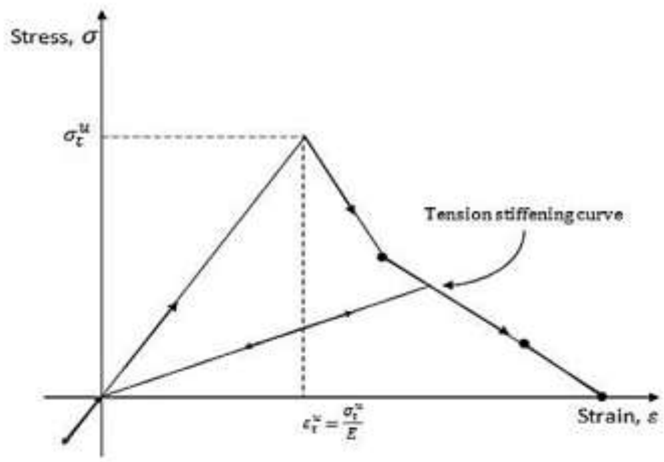


Figure 6. Stress-strain behavior of concrete under uniaxial tension [19]

2.5. Test Verification

To verify the results of finite element model in this study, we used the experimental results of Agbossou et al. [21]. Four steel-reinforced concrete slabs of $1.25 \times 1.25 \times 0.1\ m$ strengthened with CFRP strips having 5cm width were studied in their study. The spacing between the middle of each parallel CFRP strip was 10 cm (two times the strip width) bonded to the lower face of the slab using resin. The concrete was made to class C30. The steel reinforcement was made from ST65 C welded square mesh for the lower side, and ST35C welded square mesh for the upper side. They used a $500\ kN$ hydraulic jack to apply the load locally to a surface 10×10 cm in the centre of the slab. All the details of Test cases can be found [21]. They conducted bending tests by presenting load-displacement curves. Figure 7 shows a comparison between numerical results of our study and the experimental results of Agbossou et al., which indicates good consistent between them.

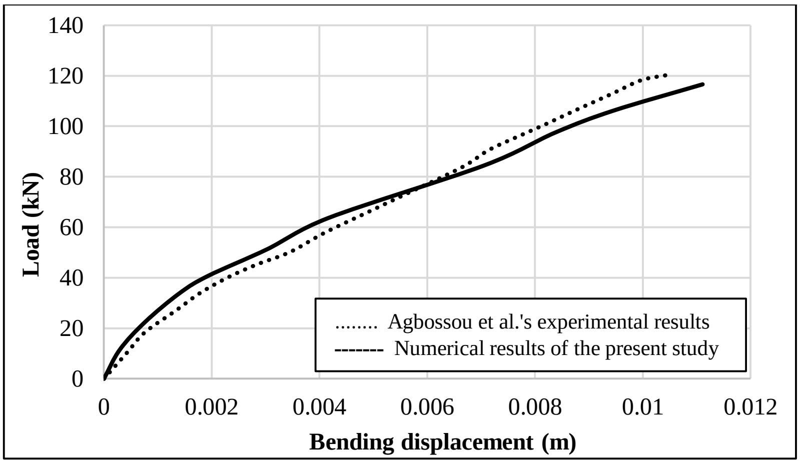


Figure 7. Numerical results of present study vs. experimental results of [21]

3. Results and Discussion

In order to analyze the behavior of RC slab strengthened with GFRP strips, the level of slab deformation was numerically investigated at a control point located at the center of slab lower side (along the center of the column) by analyzing the effects of GFRP strips' width and configurations. In addition, the maximum stresses that occur in GFRP strips due to the static loading conditions was examined considering space and width of the glass fiber strips bonded to RC slabs.

3.1. Effects of the Configurations of GFRP Strips on RC Slab Deformation

Table 3. shows deformation results of studied RC slabs strengthened by GFRP strips which were bonded to the slab surface based on three configurations by considering the strip width and space.

Table 3. Deformation results of studied RC slabs strengthened by GFRP strips bonded under three configurations

		5cm	7.5cm	10cm
PM1	0.5W	17.5548	23.0197	23.0005
	1W	20.9683	21.9794	21.5714
	1.5W	25.26	30.3717	26.1473
	2W	29.2992	29.353	38.1249
PM2	0.5W	19.1396	17.8979	18.6202
	1W	24.9564	23.0869	29.2817
	1.5W	41.2516	28.7017	30.2956
	2W	30.0531	30.3613	41.0731
DM	0.5W	19.9382	19.4309	19.5059
	1W	35.4404	28.8553	29.7351
	1.5W	29.1095	33.5102	26.6428
	2W	42.3971	38.3669	34.0208

Based on PM1 configuration, where the strips were bonded to the lower side of the slab showed that, due to the use of strips with different transverse intervals, the difference in the values of RC slab deformation was reduced such that for all three GFRP strips, there was no significant changes in the slab deformation when the space increases from 0.5 to 1W (Figure 8). The largest increase in the slab deformation was observed when the space between the 10-cm strips varied from 1.5W (15 cm) to 2W (20 cm). With PM1 configuration, the changes of the reinforced slab deformation with 5 and 7.5-cm strips were negligible.

Under PM2 configuration results showed that, by increasing the space between strips, the slab deformation level had an increasing trend. In all the transverse intervals, the lowest level of slab deformation was related to the use of 7.5-cm strips. With PM2 configuration, the least effect of glass fibers on reducing deformation of the RC slabs was related to 5 and 10-cm strips where the spaces between the strips were 1.5 and 2W, respectively (Figure 8).

Moreover, based on the results of, it can be said that if the GFRP strips were arranged according to DM model, the use of the strips could exacerbate the irregular process of slab deformation when transverse interval between 5 and 10-cm strips increases, such that when the FRP strips were placed next to each other at a space equal to their width, the slab deformation was higher than the time when the spacing was 1.5W. However, in specimens with a space of 0.5W, the width parameter did not have a significant effect on the change in deformation level occurring in the center of RC slab (Figure 8).

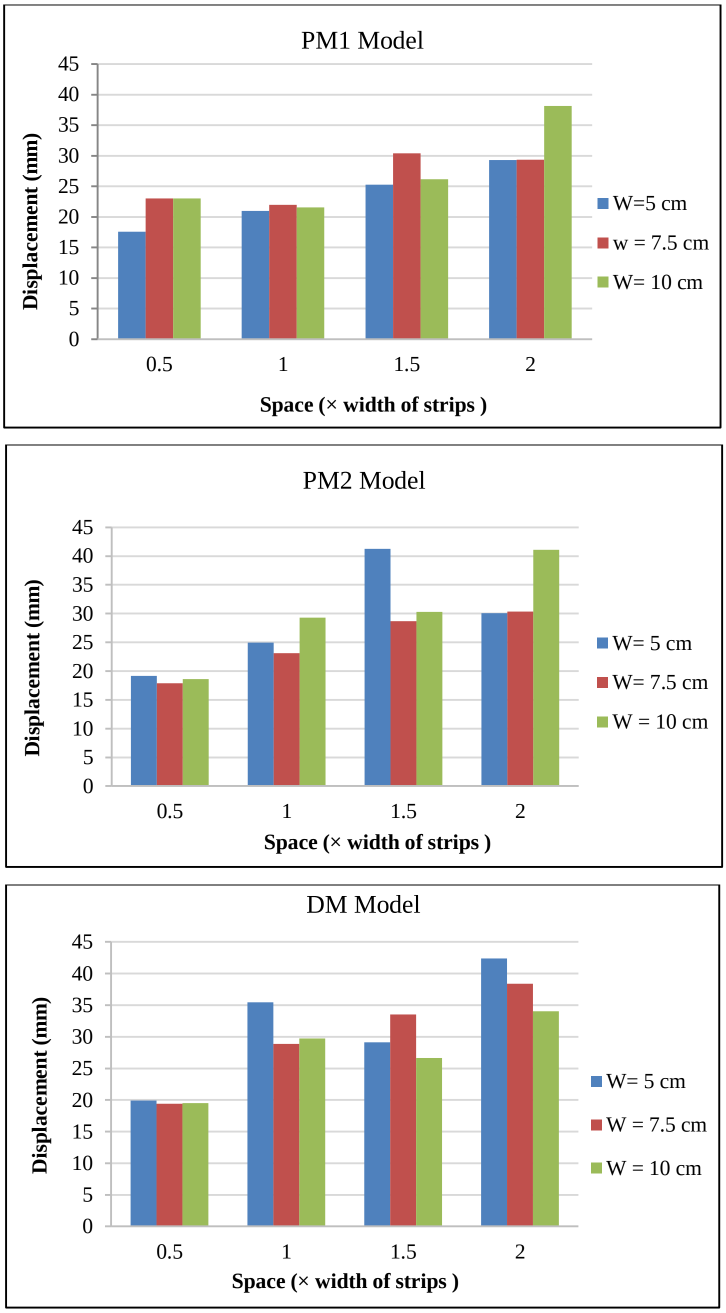


Figure 8. Comparing deformation results of studied RC slabs strengthened by GFRP strips with different configurations

3.2. Effects of the Width of Bonded GFRP Strips on RC Slab Deformation

Table 4 shows deformation results of studied RC slabs strengthened by GFRP strips with different widths of $5, 7.5,$ and $10\ cm$ considering their configuration.

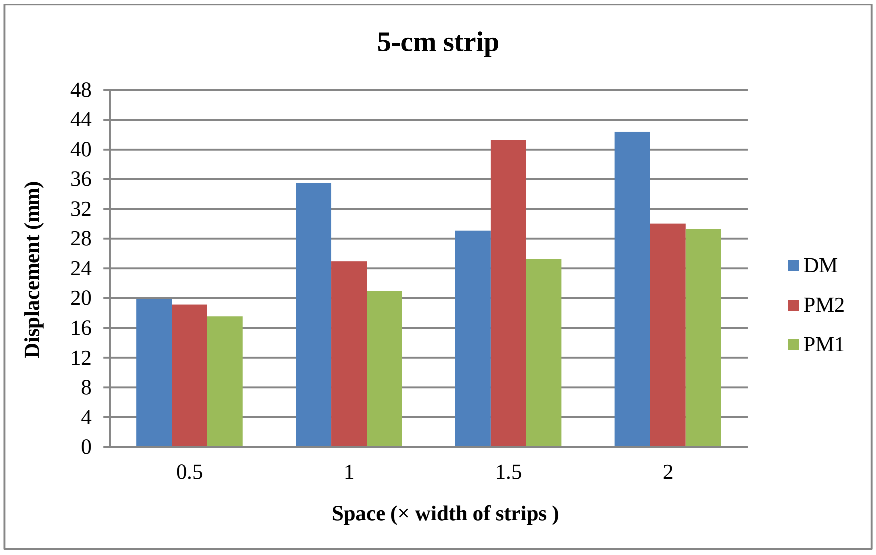
Table 4. Deformation results of studied RC slabs strengthened by GFRP strips with different widths

		DM	PM2	PM1
5 cm	0.5W	19.9382	19.1396	17.5548
	1W	35.4404	24.9564	20.9683
	1.5W	29.1095	41.2516	25.26
	2W	42.3971	30.0531	29.2992
7.5 cm	0.5W	19.4309	17.8979	23.0197
	1W	28.8553	23.0869	21.9794
	1.5W	33.5102	28.7017	30.3717
	2W	38.3669	30.3613	29.353
10 cm	0.5W	19.5059	18.6202	23.0005
	1W	29.7351	29.2817	21.5714
	1.5W	26.6428	30.2956	26.1473
	2W	34.0208	41.0731	38.1249

The results of comparing the center deformation of RC slab strengthened with three $5, 7.5,$ and $10\ cm$ GFRP strips are presented in Figure 9. Using 5-cm strips at different transverse intervals, the lowest deformation level was related to the specimens reinforced with PM1 configuration. However, except where the space between strips was 1.5W ($7.5\ cm$), the deformation level of the RC slabs was close to each other under PM1 and PM2 patterns. Based on numerical results, in the case where 5-cm GFRP strips were placed with a distance of 2W ($10\ cm$) and under the DM configuration, the deformation level of the center of RC slabs was higher compared to 7.5 and 10-cm glass fiber strips.

With the use of GFRP strips of $7.5\ cm$ in width, the trend of increasing slab deformation was fixed due to the reduce of strip number under DM and PM2 patterns. In this case, like the 5-cm strips, the highest level of deformation occurred in the center of the RC slab was related to the use of strips were under DM configuration and spaced as 2W.

Finally, according to the results, RC slabs strengthened with 10-cm GFRP strips, unlike other two stripes, the highest deformation level was observed in PM1 and PM2 configurations while the space between the strips was 2W. For each configuration of 10-cm strips, the greatest change in the slab deformation was observed when the space between strips increased from 1.5W ($15\ cm$) to 2W ($20\ cm$) while by increasing the space from 1 to 1.5W, no significant change was observed in the slab deformation level.



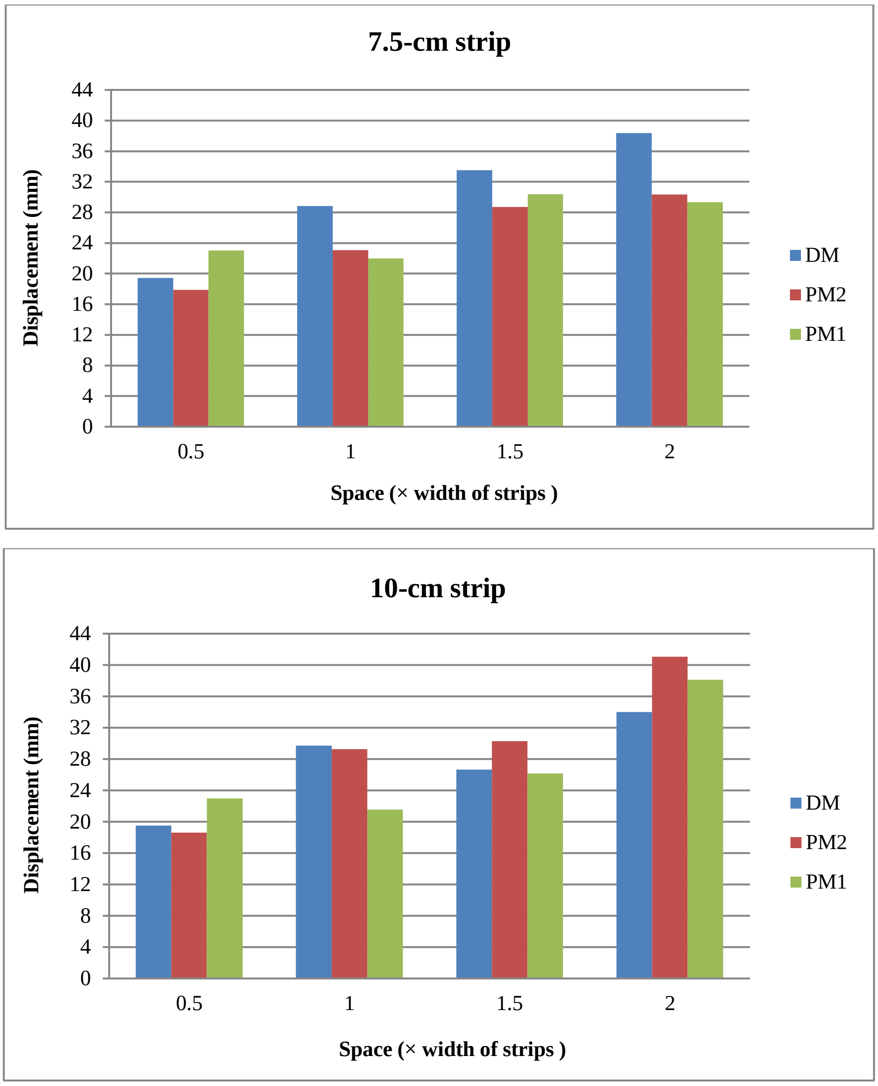


Figure 9. Comparing deformation results of RC slabs strengthened by 5, 7.5, and 10-cm width GFRP strips

3.3. Maximum Stress of GFRP Strips under Static Loading Conditions

We also obtained the results of stress occurred in studied strips when they were under static loading conditions presented in Table 5.

Table 5. Maximum stress values of specimens under static loading conditions

		5 cm	7.5 cm	10 cm
PM1	0.5W	0.3079	0.5664	0.3983
	1W	0.4463	0.4901	0.4296
	1.5W	0.4521	0.4529	0.4563
	2W	0.5494	0.4638	0.5088
PM2	0.5W	0.2614	0.2785	0.3019
	1W	0.4466	0.3879	0.413
	1.5W	0.6057	0.4348	0.4316
	2W	0.5902	0.4983	0.4777
DM	0.5W	0.3568	0.3633	0.3812
	1W	0.6216	0.502	0.6024
	1.5W	0.6441	0.5125	0.5008
	2W	0.5732	0.6116	0.5754

In Figure 10, we compared these results by considering the width, space and bonding configurations of the polymers. According to the results, the stress values of GRRP strips with different widths under PM1 configuration showed that changes in the space between the strips had a small effect on the stresses of the strips. On the other hand, in contrast to the 5 and 10-cm strips, the stress level in 7.5-cm strips decreased slightly due to the increase of space between the strips. The maximum stress values in the 7.5 and 10-cm GRRP strips were close to each other due to the bonding of strips as PM2 model at different transverse intervals. In PM2 model, the highest stress values were 0.6 and 0.95 GPa related to 5-cm strips at 1.5W and 2W transverse intervals, respectively. When RC slabs were strengthened by GFRP strips according to DM model, 5 and 10-cm strips unlike strips with a width of 7.5 cm, did not go through a regular process due to the increase in the space between the strips where among the three configurations, the highest stress level was 0.64 GPa under DM model and was related to 5-cm strips with a 1.5W space.

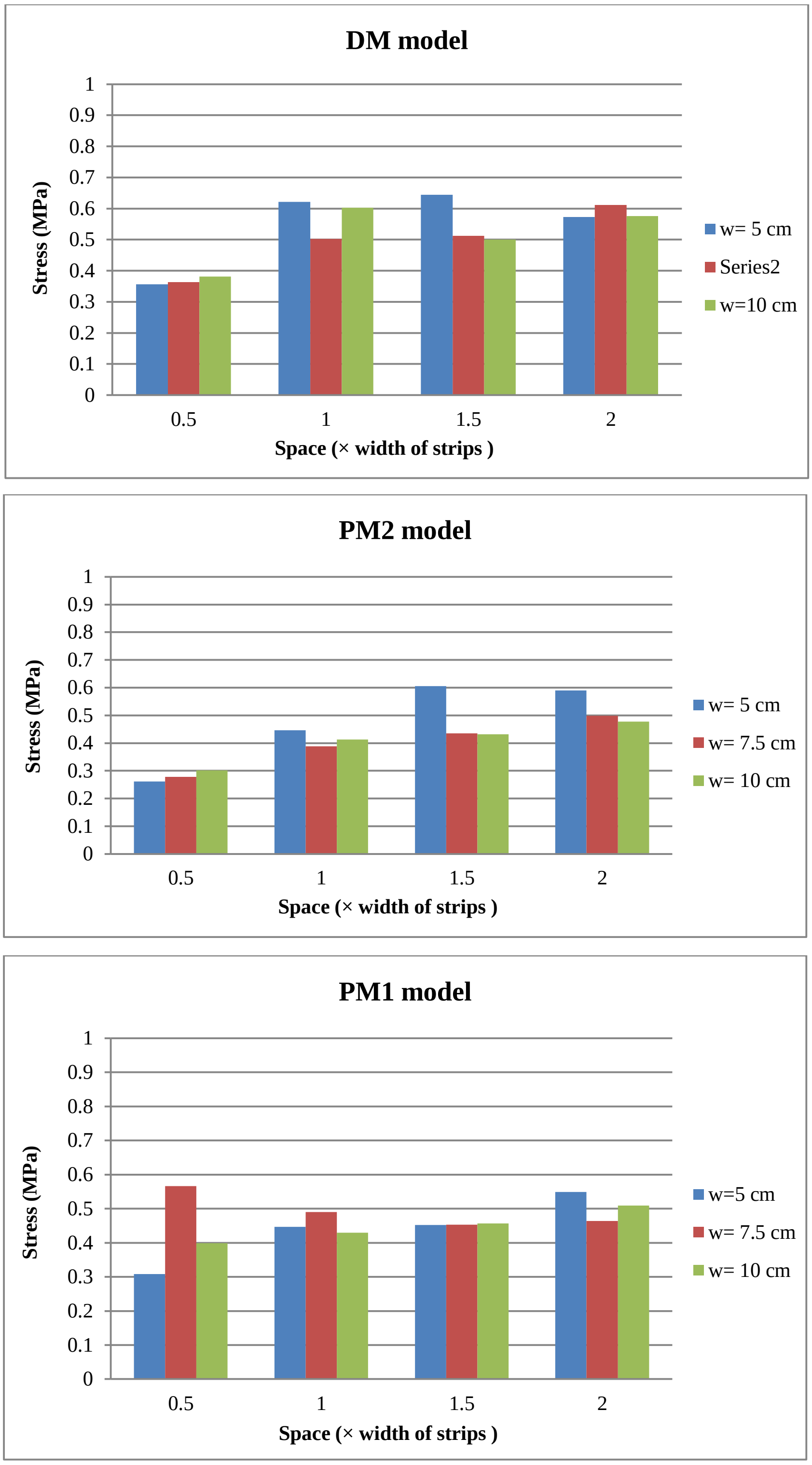


Figure 10. Comparing stress results occurring in GFRP strips with three different widths and configurations

4. Conclusion

In this paper we attempted to study the behavior of steel-reinforced concrete slabs strengthened by GFRP strips under static loading conditions using finite element analysis. The studied strips were in three widths of 5, 7.5 and 10 cm bonded to lower side of RC slabs along the longitudinal direction and arranged in three models. A total of 36 strengthened two-way RC slabs (test group) were compared to the concrete slabs with no bonded FRP strips (control group), and then the deformation of RC slabs in the center was examined with respect to the width and configuration of bonded GFRP strips.

According to the comparison results, we found out that, by using the PM2 model, the least effect of GFRP strips on reducing the deformation of slab center was related to the strips with 5 and 10 cm width where the spaces between the strips were 7.5 and 20 cm, respectively. Under DM configuration, the use of GFRP strips exacerbated the irregularity of the slab deformation as the transverse interval increases between 5 and 10-cm strips. In specimens where the space between bonded strips was 0.5 times the width of strips, strip width changes did not have a significant effect on the level of deformation occurring in the center of the slab. Moreover, we found out that by using 5-cm GFRP strips with various intervals, the lowest level of slab deformation was related to specimens in which the strips were bonded based on PM1 configuration. If the 5-cm GFRP strips are placed under the DM configuration at a space equal to two times the strip width, the deformation of slab center reaches its highest level among other specimens strengthened with GFRP strips. Based on the comparison results of specimens strengthened with 7.5-cm strips, the maximum level of slab deformation was related to the use of strips having space as two times the strip width (2W), and arranged as DM model. Moreover, in RC slabs strengthened with 10-cm GFRP strips unlike 5 and 7.5-cm ones, if the space between the strips is two times the strip width; the highest slab deformation level can be observed when strips are arranged based on PM1 and PM2 configurations.

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