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A comparative analysis of single-field concrete slabs reinforced with FRP bars

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ABSTRACT:
Fibre-reinforced composite bars (FRP) are becoming an increasingly common alternative to steel reinforcement in civil structures. The paper presents a comparative analysis of single-field concrete slabs reinforced with steel bars and FRP bars. The tested models differed in the type of reinforcement material and the diameter of the reinforcement bars. The behaviour of slab reinforced with steel bars (SRB) and composite bars made of GFRP, CFRP, BFRP and AFRP were simulated. The numerical analysis was carried out in the ADINA System program, based on the Finite Element Method (FEM). The obtained distributions of displacements and the development of cracks in the tested elements made it possible to assess the serviceability limit states (SLS) the slabs. The smallest deflections were observed for slabs reinforced with AFRP bars.

KEYWORDS:
FEM; AFRP; BFRP; CFRP; GFRP

1. Introduction

Reinforced concrete slabs are a structural element that transfers loads to beams and columns. Traditional steel bars used as reinforcement of slabs are subject to a natural and inevitable corrosion process, especially in a highly aggressive environment, which adversely affects the ultimate limit states (ULS) and serviceability (SLS) of the entire structure of concrete slabs [1]. Therefore, research is being carried out on reinforcement made of alternative materials that can minimize or eliminate corrosion in reinforced concrete structures. One of the materials characterized by the aforementioned features is a Fiber Reinforced Polymer (FRP), which was presented in [2-4]. FRP composites include: Glass Fiber Reinforced Polymer (GFRP) [5], Carbon Fiber Reinforced Polymer (CFRP) [5], Aramid Fiber Reinforced Polymer (AFRP) and Basalt Fiber Reinforced Polymer (BFRP) [6]. FRP composites are characterized by high corrosion resistance, low weight, high tensile strength, thermal insulation and fatigue resistance [7]. FRP is widely used in the design of building and engineering structures [5], e.g. as reinforcement of concrete elements in an aggressive environment [2, 8], including reinforcement of bridge decks or external elements of multi-storey buildings in the marine environment [9].

In terms of elastic deformations, FRP is characterized by a linear dependence of stresses to deformations. FRP do not show a clear degree of plasticity, unlike steel bars. Thanks to this, FRP is characterized by smaller destructive deformations and a lower elongation factor in relation to

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steel [7]. FRP rods also usually have a lower Young's modulus of elasticity than steel. The exception are CFRP and AFRP rebars, which have a modulus of elasticity close to that of steel or even higher.

Numerous tests were carried out on concrete elements reinforced with polymer rods reinforced with FRP fibres. Current directions of research concern corrosion resistance, e.g. behaviour in aggressive environments: saline solution [3] or sea water [2, 4], behaviour in standard fire conditions [9] and assessment of deflection of concrete beams and slabs [10]. Numerical calculations of concrete reinforced with FRP bars are also carried out [5, 6]. In paper [5], the behaviour of concrete slabs of bridge decks reinforced with FRP rods was simulated. For this purpose, a non-linear numerical analysis using three-dimensional finite elements (NLFEA) was used. The tests carried out showed that the use of reinforcement made of CFRP and GFRP bars allowed to obtain better results of breaking load, stiffness in the elastic range, stiffness after cracking compared to slabs with steel reinforcement. At the same time, reinforcement with CFRP and GFRP rods had only a slight effect on the limit deflection in comparison with steel reinforcement.

2. Aim and scope of work

The aim of the work was to analyse the serviceability limit state SLS (cracks and deflections) of single-field concrete slabs, fixed around the perimeter, reinforced with composite bars (Fig. 1).

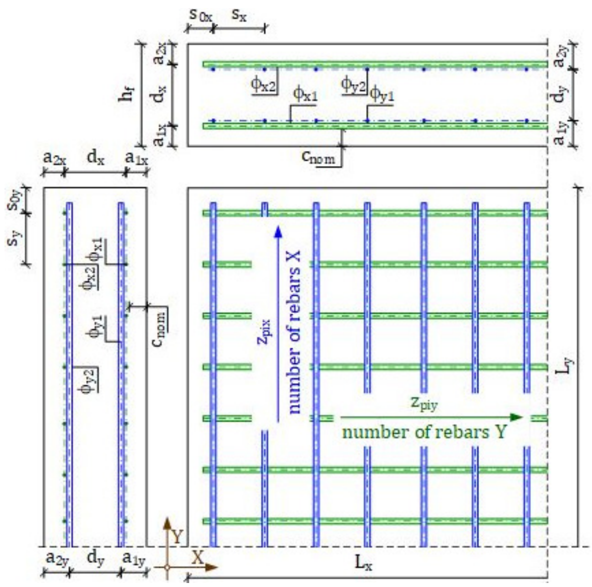

Fig. 1. Graph of reinforcement of concrete slabs analysed using numerical models

The subject of the work was slabs with dimensions of 6000 × 6000 mm and a thickness of 200 mm, made of concrete class C20/25 with a modulus of elasticity E_{cm} = 30 GPa. The material data of the concrete were adopted on the basis of EN 1992-1-1 [11]. SRB, GFRP, CFRP, AFRP, BFRP rebars (Fig. 2) with diameters of ø = 12 mm, ø = 10 mm, ø = 8 mm in spacing of $sx = sy$ = 100 mm were used for two-way reinforcement of the slabs. The lower reinforcement was placed over the entire surface of the slab and the upper reinforcement was placed around the perimeter in a strip 1200 mm wide. Reinforcement material data are presented in Table 1. The following slab models were analysed:

- model of a concrete slab without reinforcement in the compression and tension zone (as a reference model),
- model of a concrete slab with a classic reinforcement of SRB steel bars,

- model of a concrete slab with GFRP reinforcement,
- model of a concrete slab with CFRP reinforcement,
- model of a concrete slab with AFRP reinforcement,
- model of a concrete slab with BFRP reinforcement.

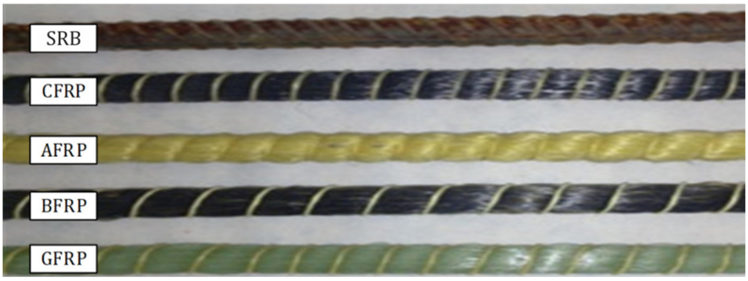

Fig. 2. Types of reinforcing bars used in concrete slab models

Table 1
Properties of applied reinforcing bars

Type of rods	Material data		
	Young's modulus E [GPa]	Poisson's ratio	Density [kg/m^3]
Steel bars	200.00	0.30	7850
Aramid fiber rods (AFRP)	175.00	0.35	1440
Basalt fiber fods (BFRP)	39.05	0.30	2000
Carbon fiber fods (CFRP)	150.00	0.30	2000
Fiberglass rods (GFRP)	50.00	0.22	1900

The calculations assumed construction class S4 according to EN 1992-1-1 [11] and XC3 exposure class for moderate environment according to EN 206 [12]. For the selected exposure class, the minimum cover required due to the durability of the reinforcing bars was assumed to be $c_{min,dur}$ = 25 mm and deviations related to the element manufacturing technology Δ_{cdev} = 10 mm. The nominal cover for the reinforcing bars was assumed to be c_{nom} = 35 mm.

The analysed slabs deflections at three load variants: self-weight, load of 10 kN/m^2 corresponding to a very heavily loaded warehouse floor, and 100 kN/m^2 to illustrate the destruction of the slab.

The analysis was carried out based on the results of calculations carried out in the Adina System program. A parametric numerical model for solving problems associated with nonlinear analysis involving large deformations, material nonlinearities was developed. All degrees of freedom were taken away on all 4 edges of the slab. The pressure representing the variable load was act along the Z axis. A special concrete material model available in ADINA System with the uniaxial stress-strain data was used. The plastic-bilinear material model was used for simulation of rebar elements.

3. Results and discussion

Based on the numerical analysis, the deflection values of the concrete slab without reinforcement and the concrete slab reinforced with the analysed bars: BFRP, GFRP, CFRP, AFRP and SRB, from the given loads, were obtained. For each of the models, the type and location of cracks were also obtained. The results of the size of displacements and the type of cracks for the concrete slab reinforced with ϕ = 12 mm SRB bars are shown in Figure 3. Distribution of displacements indicates that the slab does not sag around the perimeter. What is the effect of slab restraint. The maximum deflections occur in the middle of the slab span. However, on the basis of the distribution of cracks (Fig. 3c), it was observed that during the application of a load of 10 kN/m^2 on the upper surface of the panel, in the area of the middle part of the edge, there are cracks marked no. 1, which corresponds to open cracks. During the application of the load of 100 kN/m^2 (Fig. 3d) on the upper surface of the slab, there are no cracks only in its central part and corners. In the remaining area, open cracks (no. 1), closed cracks (no. 2) and concrete crushing (no. 3) can be observed.

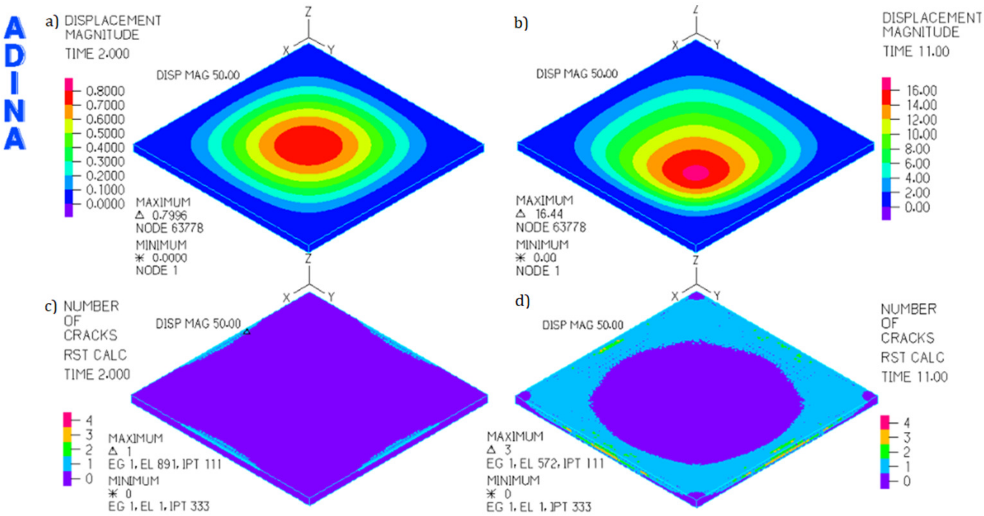

Fig. 3. Results of numerical analysis of slab reinforced with ϕ = 12 mm steel bars: a) displacement distribution at load of 10 kN/m^2, b) displacement distribution at load of 100 kN/m^2, c) type and location of cracks at load of 10 kN/m^2, d) type and location of cracks at load of 100 kN/m^2

The results of the numerical analysis were presented in column charts (Figs. 4-6). The vertical axis represents the percentage values of the reinforced slab deflection in relation to the unreinforced concrete slab deflection, treating it as a reference value of 100%. The horizontal axis shows the reinforcement factor calculated as the ratio of the volume of reinforcing bars to the volume of concrete, multiplied by 100%:

$$r_c = \frac{V_{rb}}{V_c - V_{rb}} \cdot 100\% \tag{1}$$

where:
r_c – reinforcement coefficient,
V_{rb} – volume of reinforcing bars,
V_c – volume of concrete.

The deflection of the concrete slab without reinforcement due to self-weight, 10 kN/m^2 and 100 kN/m^2 loads was 0.2618 mm, 0.8213 mm and 23.71 mm, respectively. In each of the analysed slabs, the deflection caused by the load of 10 kN/m^2 did not exceed the maximum permissible deflection according to EN 1992-1-1 [11], which is 1/250 of the span, i.e. 21.6 mm.

Figure 4 shows deflections due to self-weight. The deflections of the slabs reinforced with the analysed bars are up to 2.5% lower than those of the non-reinforced slab. The values of deflections due to dead weight and from the load of 10 kN/m^2, obtained in numerical calculations, were checked analytically, according to the calculation formulas presented in [13]. The results were consistent.

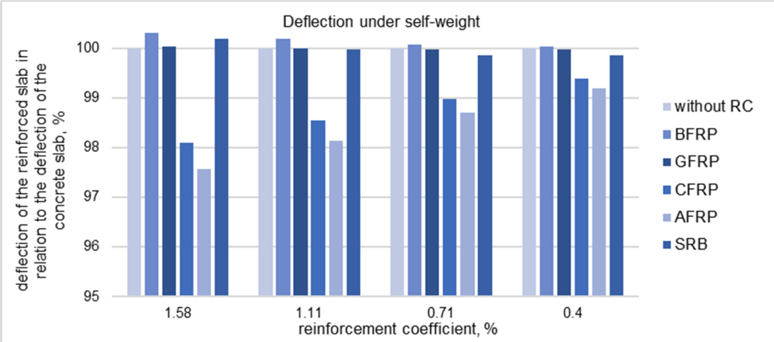

Fig. 4. Self-weight deflection diagram

Figures 5 and 6 show deflections of concrete slabs and reinforced slabs under loads of 10 and 100 kN/m². The following dependence can be seen in both diagrams: the lower the reinforcement coefficient, the greater the deflections of the slabs and they approach the value of the deflection of concrete slabs. For both load cases, the highest deflection values were obtained for slabs reinforced with BFRP and GFRP bars, for which the assumed Young's modulus (respectively: 40 and 50 GPa) is the closest to the modulus of elasticity of concrete (30 GPa).

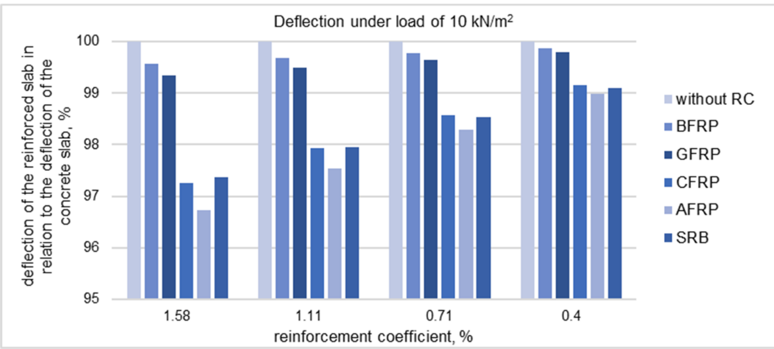

Fig. 5. Deflection diagram under load 10 kN/m²

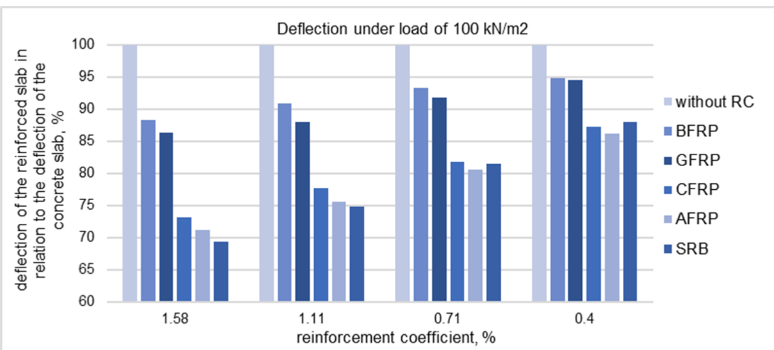

Fig. 6. Deflection diagram under load 100 kN/m²

At a load of 10 kN/m² (Fig. 5), the smallest deflections were observed for slabs reinforced with AFRP bars, for which the assumed Young's modulus (175 GPa) is similar to the Young's modulus of steel (200 GPa). However, the density of AFRP is 5 times lower than that of steel.

As the reinforcement coefficient decreases, the differences between the deflections of slabs reinforced with AFRP and SRB bars decrease. With a reinforcement factor of 1.58%, the difference is 0.63 percentage points, while with a factor of 0.4% it is equal to 0.12 points. This is due to the reduction of the stiffness of the slab along with the reduction of the volume of the adopted reinforcement.

At a load of 100 kN/m^2 (Fig. 6), with a reinforcement coefficient of 1.58% and 1.11%, the smallest deflections were achieved by the slab reinforced with SRB bars, while at the coefficient of 0.71% and 0.4%, the slab reinforced with AFRP bars. Differences in the value of deflections of slabs reinforced with bars: CFRP, AFRP and SRB, regardless of the amount of reinforcement in relation to the deflection of the concrete slab, do not exceed 4 percentage points.

4. Conclusions

– During the application of the load of 10 kN/m^2, the deflections of the slabs reinforced with the analysed bars are up to 3.5% smaller in relation to the non-reinforced slab.
– The smallest deflections were observed for slabs reinforced with AFRP rods, for which the adopted Young's modulus (175 GPa) is close to the Young's modulus of steel (200 GPa), but the density of AFRP is 5 times lower than that of steel.
– As the reinforcement coefficient decreases, deflections of slabs reinforced with CFRP, AFRP and SRB become similar.
– Crack initiation in concrete occurs under a load of 10 kN/m^2 and can be observed in the form of open cracks located on the even surface of the slab, in the area of the center of the restrained edges.

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Analiza porównawcza płyt betonowych jednopolowych zbrojonych prętami FRP

STRESZCZENIE:
Pręty kompozytowe wzmacniane włóknami (FRP) stają się coraz częstszą alternatywą zbrojenia stalowego w konstrukcjach budowlanych. W pracy przedstawiono analizę porównawczą jednopolowych płyt betonowych zbrojonych prętami stalowymi oraz prętami FRP. Badane modele różniły się rodzajem materiału zbrojenia i średnicą prętów zbrojeniowych. Symulowano zachowanie płyt zbrojonych prętami stalowymi (SRB) i prętami kompozytowymi GFRP, CFRP, BFRP oraz AFRP. Analizę numeryczną przeprowadzono w programie ADINA System, opartym na metodzie elementów skończonych (MES). Uzyskane rozkłady przemieszczeń oraz rozwój zarysowań w badanych elementach pozwoliły na ocenę stanu granicznego użytkowalności płyt. Najmniejsze ugięcia zaobserwowano dla płyt zbrojonych prętami AFRP.

SŁOWA KLUCZOWE:
MES; AFRP; BFRP; CFRP; GFRP