Stress Analysis of Slabs Reinforced with GFRP Rebar

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Abstract. Designed constructions must meet a certain level of safety and durability. They should also be designed in accordance to Ultimate Limit State and Serviceability Limit State with respect to profitability for the contractor. During designing stage of reinforced concrete, it is important to remember that the values in static and strength calculations are assumed as ideal. In reality, material properties of steel and particularly concrete are biased with a certain degree of random. Modern technologies allow to utilize construction materials with strictly determined deformation and mechanical parameters. Significant development of concrete technology in recent years poses new challenges. In the study, authors used Glass Fibre Reinforced Polymer rebar as a replacement for standard steel rebar. The article presents the results of the destruction tests of concrete slabs reinforced with steel and GFRP rebar. The tests were performed on 14 slabs with length-to-width ratio of 4. The thickness of slabs ranged from 6 to 10 cm. In nine slabs, authors replaced the standard rebar with GFRP rebar. The tests involved stress analysis in rebar and concrete. The secondary goal was to determine the bearing capacity and deflection of slabs and assess the cracking of the sections during load application. Composite rebars have many advantages over standard rebar. However, due to a relatively low elasticity modulus in comparison to steel, the slabs exhibit excessive deflection and cracking of bent elements.

1. Introduction
Modern civil engineering facilitates the use of high-performance materials. The projects must develop according to the highest standards in the shortest time possible. Those requirements impose the requirement of using novel solutions. Modern technologies in civil engineering are used to increase the effectiveness of performed work.

Concrete is one of the most common building materials. It exhibits excellent load-bearing properties. Naturally high compressive strength is complemented with additional rebar to increase the tensile strength. In monolithic reinforced concrete, the rebar is mostly made of steel. However, in recent times alternative solutions are more often implemented.

During designing stage of reinforced concrete, it is important to remember that the values in static and strength calculations are assumed for a perfect case. In reality, material properties of steel and particularly concrete are biased with a certain degree of random. Modern technologies allow to utilize construction materials with strictly determined deformation and mechanical parameters.

Cost-optimal designing can lead to the changes in the dimensions of the bearing element, replacement of the steel with composite rebar or simultaneous use of steel and composites. Use of composite rebar can lead to optimization of the construction [1]. Composite rebars are a proper solution in case of constructions exposed to aggressive surroundings due to their resistance to corrosion and significant fatigue resistance [2].
Composite rebar consists of continuous fibres covered with a polymer resin. The main role of the fibres is to provide high strength and rigidity of the element. The resin binds the fibres and retains the proper space between them, providing additional protection from outside damage. Depending on the type of the fibres, there are four main types of the Fibre Reinforced Polymer (FRP) rebars: carbon fibre (CFRP), aramid fibre (AFRP), glass fibre (GFRP), basaltic fibre (BFRP). To produce the composite, the fibres are immersed in a thermosetting or thermoplastic resin.

2. Materials
The composite is a material consisting of several different substances bonded together that can be mechanically separated from each other. The components are placed in a controlled way to give optimal properties. The composite has unique properties that are often better than the properties of individual components.

The binder is often called warp or a matrix. The warp incorporates fibres or grains that are used as fillers, strengtheners and reinforcement. To produce the strengthening effects, the composite has to contain a proper amount of reinforcement. The binder guarantees cohesion, rigidity, elasticity and compressive strength, while the strengthening components enhance the mechanical properties of the composite.

The composite rebar has numerous advantages, including low bulk density (approximately four times lower than steel), and no electric conductivity. Additionally, corrosion resistance and low thermal conductivity have an important application in civil engineering.

The fibres used for the production of rebar composites can be distinguished by the manufacturing process. The fibres can be obtained from natural, mineral, plant resources or produced artificially. The most commonly used fibres are the glass fibres. The effectiveness of the fibres depends on the specific strength – a ratio of the tensile strength and specific density – and the specific modulus – ratio of the elastic modulus to specific density. The higher the ratios, the more effective the fibres [3,4].

The GFRP rebar can be used in an aggressive environment where the standard steel is exposed to corrosion. The glass fibre rebars are resistant to acids, salts and defrosting agents [1]. Therefore, they can be utilized in road and water projects. The GFRP rebar is a perfect electric insulator, which can be useful in power plants and transformers. The GFRP rebar, in opposition to steel, does not transmit heat and electromagnetic waves. This allows to utilize the rebar in research facilities, hospitals and industrial plants, where conductive materials can have a negative effect on work of different equipment. Other important aspect is the proper cooperation between the composite and the concrete. Therefore, it is important to comply with the recommendations of the producers to acquire the proper rebar-concrete adhesion.

The GFRP rebar does not have a negative effect on human body and surrounding environment. The rebar is nontoxic and easy to dispose. Old or damaged elements are easier to dismantle and produce less waste than sections with steel rebar. The energy used for production of a composite rebar is almost four times lower than in case of steel rebar production. Unique characteristics of GFRP rebar allowed to increase its usage in civil engineering.

2.1. General strength properties of GFRP rebar
The strength of a compressive rebar depends mostly on the type of used fibres and employed matrix. The production method also influences the mechanical parameters of the composite rebar.

The differences in the strength of the rebar come from the cross section and arrangement of the fibres. Rounded rebar with ribbed cross-section made from glass fibres arranged in a parallel manner can be subjected to tearing of the surface. Rebars immersed in the epoxy resin have higher dimensional variability.

Current research allowed to state that the tensile strength of composite rebar reinforced with glass fibres is more than two times higher than the steel rebar. The compressive strength equals to approximately between 20-70% of the tensile strength. Significant difference between the compressive and tensile strength shows that it is not an applicable material for use in compressed areas of the cross-
section. Additionally, the failure of the rebar occurs without earlier signs, with rapid rupture in the tensile tests [5,6].

### Table 1. The mechanical properties of GFRP and steel bars

| Material                  | GFRP bars          | Steel bars        |
|---------------------------|--------------------|-------------------|
| Yield point/tensile strength [MPa] | 1000 - 1500       | 440 - 550         |
| Elastic modulus [GPa]     | 50 - 60            | 200 - 210         |
| Unit elongation [%]       | 1.5 - 2.2          | 10 - 25           |
| Deformation [%]           | 30                 | 2.18 - 2.72       |
| Density [g/cm³]           | 2.2                | 7.85              |

### 3. Scope of the study

The laboratory tests were performed on fourteen concrete slabs with 120 cm length, 30 cm width and varying thickness between 6 cm – 9.5 cm. In nine of the produced slabs, the rebar was made of GFRP, while in five the steel rebar was used. Performed analysis started with determination of the deflection using Hooke’s Law for deriving the stresses. Next step was to compare the acquired results of stresses, bearing capacity and deflection in the slabs with the same thickness but a different rebar.

### 4. Composite rebar

To reinforce the slabs, authors used the GFRP rebar produced by Armastek Company with a diameter of Φ 6 mm. The rebar grid was manually produced from 3 longitudinal bars separated with perpendicular bars at the ends. The Armastek Company provides rebars in coils of any length. For study purposes, authors used 50 m long coil. Due to low weight and easy processing, working with GFRP bars is easier with lower montage costs compared to the steel bars.

![Figure 1. Bars with glued gauges](image1)

![Figure 2. The GFRP rebar grid in the formwork](image2)
The producer recommends to use the rebar in housing developments, offices and industrial projects for reinforcement of foundations, slabs and beams. On the Russian market, the company implements their products for road and bridge constructions, in aggressive and cold environments.

5. Test bench
The test bench for strength tests of slab specimen consisted of two supports with a span of 100 cm. The strain gauges were attached to the compressive zone of the slabs to determine the deformation during load application. Two concentrated forces were applied to the slabs with a span of 33.3 cm from the supports.

![Test bench](image1)

**Figure 3.** Test bench

To measure the deflections, digital gauge was installed. At each force threshold, the measurements of the gauge were recorded and the occurring of cracks was analysed, including their depth and width.

![Deflection of the slab](image2)

**Figure 4.** Deflection of the slab reinforced with GFRP rebar
The load was increased until failure of the element. During the test, the initial force threshold as well as the increment was changed to increase the precision of the results.

In the early stages of tests, it was noticed that the slabs reinforced with composite rebar exhibited significantly higher deflections. The GFRP rebar reinforced slabs exhibited the deflection of up to 70 mm.

![Figure 5. Destruction of the slab reinforced with steel rebar](image1)

![Figure 6. Destruction of the slab reinforced with GFRP rebar](image2)

6. Results

Based on acquired strength test results, the curves of stress development in the rebar and concrete were generated. The results are presented in figures 7 and 8. Each figure presents the comparison between slabs with the same thickness but a different rebar (either steel or GFRP). The analysis of stresses in concrete and rebar is presented separately. The analysis of the figures 7-9 allowed to state that the slabs reinforced with standard steel have a higher tensile strength than slabs reinforced with GFRP rebar due to almost two times higher reinforcement area. In case of the GFRP rebar, the authors noticed multifold increase of the stresses in concrete and several dozen higher stresses in rebar after reaching the cracking point. In case of the slabs reinforced with steel rebar, the increase of those stresses was milder, however after exceeding the cracking moment increase of stresses was recorded.

The failure of the slabs reinforced with steel proceeded due to rupture of the bars, while failure of the slabs reinforced with composite rebar occurred due to exceeding bearing capacity of the concrete.
Figure 7. Comparison of bearing capacity and stresses in the rebar in slabs reinforced with composite and steel rebar.

Figure 8. Comparison of bearing capacity and stresses in the concrete in slabs reinforced with composite and steel rebar.

The analysis of figures 4-8 allows to state that the failure of slab reinforced with composite GFRP rebar is significantly dependant on the low elasticity modulus (approximately 50 - 60 GPa). This results in a lower stiffness of the cross-section after cracking and a visible leap in the stresses measured in rebar and concrete.

As a result of high tensile strength of the GFRP rebar and preferable failure process (crushing of concrete in compression zone), it is necessary to perform tests on High-Performance Concretes. There is, however, an issue with Serviceability Limit State regarding deflection control and cracking control as key elements in the analysis of the bended concrete elements. High bendability of the element creates...
a complex system of forces in the rebar. The failure of the elements reinforced with GFRP rebar is caused by complex processes that include: cracking of the matrix, tearing of fibres, propagation of cracking and stratification of the composite.

Figure 9 presents the development of the deflections in tested slabs depending on applied force. The figure presents the slabs with similar thickness reinforced with steel and composite rebar.

![Figure 9. Deflection of slabs reinforced with composite and steel rebar](image)

The analysis of the results showed similarities between development of the deflections in tested slabs and development of the stresses. After reaching the cracking moment, slabs reinforced with GFRP rebar exhibited a rapid increase of the deflection which caused crushing of the concrete in the compression zone. Simultaneously the bearing capacity of the element is not fully employed. The destruction occurs suddenly, without previous signs. The failure occurred by bending-shearing destruction that proceeds by revealing the rebar and sudden rupture.

7. Conclusion
Conducted laboratory tests on the influence of composite rebars on the properties of slab elements allowed to draw following conclusions:

- It was noticed that the type of used rebar has an influence on the development of stresses in slabs both in rebar and concrete. The slabs reinforced with composite rebar exhibited several times higher values of the stresses in concrete and several dozen times higher values of stresses in rebar after exceeding cracking moment. The increase of stresses in rebar and concrete in case of slabs reinforced with the steel was milder than in slabs reinforced with composite rebar.
- Slabs reinforced with the composite rebar exhibited lower stiffness after cracking due to low elasticity of the composite rebar and much higher depth of cracks.
- It was shown that the type of used rebar has an influence on the development of deflection during load application for slabs with the same cross-section. The slabs reinforced with the composite rebar exhibited a higher increment of deflection after reaching the cracking moment. High deflection of the slabs reinforced with composite rebar was a result of assumed degree of reinforcement. The deflection of 6 cm thick slabs reached 7 cm on a span of 100 cm.
increase of the deflection in case of slabs reinforced with steel was lower than for slabs reinforced with a composite rebar.

- It was observed that the lower stiffness of GFRP rebar causes the occurrence of more significant cracking. The cracks are more numerous and wider than in slabs reinforced with steel rebar.
- The failure of the slabs reinforced with the steel rebar occurred by rupture of the bar, while the failure of the elements reinforced with the composite rebar occurred due to the crushing of the concrete in the compression zone, while the bearing capacity of the composite was not fully exploited. The destruction occurs suddenly.
- The dimensions of the cross section should be assumed based on the deformation of the element, bearing in mind the linear elastic properties of the composite and limit deformation. High elongation of the rebar results in the reduction of the compression zone.
- Serviceability Limit State (SLS) plays a more significant role in case of the elements reinforced with composite rebar than elements with steel bars.
- To determine precisely the influence of rebar type, it is necessary to analyse the elements with High-Performance Concrete. Comparison of the elements with a higher degree of reinforcement should also be performed.

To sum up, utilizing the composite rebar as an alternative to the steel reinforcement requires a detailed analysis of the calculation methods. Excessive deflections of the slabs can limit the area of use. It might also happen that the designed slabs with a composite rebar will not meet the serviceability requirements. Thanks to an increasing popularity and unique properties, the composite rebars have a chance to become an interesting alternative to standard steel rebars.

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