Parametric Study of Concrete Members with GFRP Reinforcement Subjected to Bending and Axial Force

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Abstract. The paper deals with the possible replacement of steel reinforcement by GFRP reinforcement for concrete elements subjected to bending moment and compressive axial force. For the last 15 years, Fibre Reinforced Polymer (FRP) bars became more popular and commercially available as reinforcement for concrete elements. Composite FRP materials are still new in construction and many engineers are not familiar with their properties and behaviour. FRP has certain advantages over steel reinforcement. It is a durable material that is not subject to corrosion, does not conduct heat, is an electrical insulator and conducts electrical current, and is non-magnetic. In contrast, FRP also has certain deficiencies such as sensitivity to higher temperatures, alkaline environments, and reduction of mechanical properties at high levels of long-term stress. In the case of FRP reinforcements, the plastic branch is missing in the $\sigma$-$\varepsilon$ diagrams, what leads to a sudden failure of the reinforced concrete element, either by tensile rupture of the reinforcement or by crushing the concrete. The most used FRP reinforcement is made of glass fibres - GFRP reinforcement. The paper deals with the possible replacement of steel reinforcement by GFRP reinforcement for slab and beam elements. The text describes a parametric study for different reinforcement ratio with GFRP reinforcement and steel reinforcement. The study is performed for a cross-section of 500x500 mm for a column element and a cross-section of 1000x250 mm for a slab element. The effect of longitudinal GFRP reinforcement in elements under compression was investigated. The study contains a comparison of interaction P-M diagrams of concrete elements with steel and GFRP reinforcement. For design GFRP reinforced concrete elements, it is necessary to consider different material characteristics such as tensile strength and modulus of elasticity. The contribution of the GFRP reinforcement in compression was neglected due to the anisotropic nature of the GFRP reinforcement and the low modulus of elasticity. The main reference basis for the elaboration of a parametric study is the fib Bulletin No. 40.

1. Introduction
For the last 15 years, Fiber Reinforced Polymer (FRP) bars became more popular and commercially available to reinforce concrete. The basic element of FRP reinforcement is fibers. The common fibers used for the production of FRP bars are glass, carbon, aramid, and basalt. The most used reinforcement is made of glass fiber, the so-called Glass Fiber Reinforced Polymer (GFRP). There exist different types of glass fibers; the common fibers are E-glass (electrical glass), A-glass (window glass), AR-glass (alkali-resistant glass), and S-glass (structural/high strength glass). The FRP bars are behaving linearly elastic until they reach tensile strength [1]. Surface treatment GFRP is either sandcoating or wrapping, figure 1.
GFRP is an excellent thermal and electrical insulator that has high tensile strength and low weight. These assumptions make them a possible substitution for steel reinforcement. Also, GFRP do not corrode for that are suitable for structures with high humidity and aggressive environment. GFRP is easier to handle due to its low weight.

Opposite their positive properties, which GFRP offer, they are characterized by a brittle failure. Rupture is caused by the absence of the plastic branch in the $\sigma$-$\varepsilon$ diagram. Failure of the concrete element comes suddenly in two ways: by crushing concrete in the compression zone of an element or tensile rupture of the FRP reinforcement. Failure of the element is not indicated by accompanying characters, excessive deflection, and cracks, as for elements reinforced with steel reinforcement [2]. Another drawback and uncertainty with designing is the impact of an alkaline environment, which decreases the long-term strength of GFRP bars [3].

In the article is analyzed resistance of element subjected to bending and axial force. Basis of calculation is a method according to fib Bulletin 40: FRP reinforcement in RC structures [1]. Method of calculation resistance of element by reinforced GFRP is similar to steel reinforced element. However, a compressive contribution of GFRP is markedly less than steel reinforcement. This addition can be neglected. The impact and influence of compression GFRP are described in more detail in chapter 2. The paper contains a parametric study of different cross-section subjected to bending and axial force. Analysis was performed for a column element and slab element. The cross-section resistance of a column element is an example of the stress state of a compression column or pile. The slab element is an example of a cross-section used e.g. in a tunnel lining. For column element was used a cross-section of 500×500 mm, and for a slab element was used a cross-section of 1000×250 mm reinforced by GFRP and steel reinforcement. The study was performed for various reinforcement ratios from lowest value 0.4 % to highest value 4.0 %.

![GFRP bars – wrapping and sandcoating surface](image)

**Figure 1.** GFRP bars – wrapping and sandcoating surface

2. **Compressive behaviour of GFRP**

The compressive resistance of composite reinforcement is very questionable. Some authors considering the compression contribution of GFRP bars. B. Bennokrane states that the compressive strength of GFRP rebars is approximately 40 to 60 % of tensile strength [4]. Kobayashi suggested to consider the compressive strength of GFRP bars, like 35 % of tensile strength [5]. Compressive strength in bars $P_0$ can be calculated by equation 1:

$$P_0 = 0.85f_c(A_g - A_f) + 0.35f_{ftu}A_f$$ (1)

where $f_c$ is the concrete compressive strength; $A_g$ is the cross-section area of concrete; $A_f$ is the total cross-section area of longitudinal GFRP bars, and $f_{ftu}$ is the tensile strength of the GFRP bar.
Tobbi stated that ignoring the compressive contribution of the GFRP bars underestimates the maximum axial capacity [6]. A newer equation was derived, which considering compression contribution based on elastic theory and from material properties:

\[ P_0 = 0.85f_c (A_g - A_f) + \varepsilon_0 E_f A_f \]  

(2)

when \( \varepsilon_0 \) is the concrete strain at peak stress, and \( E_f \) is the modulus of GFRP reinforcement's elasticity.

However, there does not exist a testing standard for determining the compression behaviour of GFRP reinforcement. Several researchers tested the compression behaviour of GFRP bars by the ASTM D695 test procedure. Premature splitting was observed due to high-stress concentration at the ends, which propagated through the bars' entire length. Due to this fact, the procedure was modified by inserting the reinforcement ends into the steel tubes. After splitting failure, the bar sample was cut vertically at the contact point. It was suggested that the ends of bars be sealed by epoxy resin. The design showed a failure to crush at the ends of the reinforcement due to epoxy resin's softness [7]. In the article [7] has been proposed a new test procedure in determining compressive properties of GFRP reinforcement. Both ends of bars were inserted into the steel caps, with a cement grout filling the gap. Tests were performed on bars of three different diameters \( d_b \) and three different lengths \( L_u \). The test provided that smaller diameter bars have almost similar compression strength as tensile strength. In contrast, bigger diameter bars failed at a compressive stress of 75% and 65% of their tensile strength. Ratio \( L_u/d_b \) is significant in the compressive strength of GFRP bars.

This study does not consider the compression contribution of GFRP bars according to the recommendation of the manual fib Bulletin 40: FRP reinforcement in RC structures [1].

3. Parametric study of P-M diagrams

3.1. fib Bulletin 40: FRP reinforcement in RC structures

Failure of elements reinforced with GFRP reinforcement can occur by pressure crushing of concrete or tensile rupture of reinforcement. When would theoretically occur by crushing of concrete and rupture of reinforcement, the condition is called the reinforcement ratio for balanced sections, \( \rho_{fb} \). In the case of only bending moment, this condition is determined by balanced reinforcement ratio, using the equation 3:

\[ \rho_{fb} = 0.81 \left( \frac{f_{ck}}{f_{fk}} + 8 \right) \varepsilon_{cu} \]  

(3)

When the amount of longitudinal FRP reinforcement, \( \rho_f \) is lower than \( \rho_{fb} \), flexural failure is expected to occur due to GFRP rupture, and the ultimate moment resistance (\( M_u \)), can be calculated by equation 4:

\[ M_u = \frac{A_f f_{fk} \gamma_f}{d - \frac{\varepsilon_0 \cdot d}{2}} \]  

(4)

When the amount of longitudinal FRP reinforcement, \( \rho_f \), is higher than \( \rho_{fb} \), flexural failure is expected to occur due to concrete crushing, and the ultimate moment resistance \( M_u \), can be calculated by equation 5:

\[ M_u = \eta f_{cd} b d^2 (\lambda \xi) \left( 1 - \frac{\lambda \cdot \xi}{2} \right) \]  

(5)

Moment resistance grows with the strength of concrete and the amount of FRP reinforcement. It is necessary to determine a minimum limit on the amount of longitudinal reinforcement to obtain a greater
resistance moment than the reinforced section's cracking moment. The minimum reinforcement area is determined using equation 6:

\[ A_{f, \text{min}} = 0.41 \frac{f'_c}{f_{fu}} b d \geq \frac{2.26}{f_{fu}} b_w d \]  

(6)

3.2. Parametric study

The parametric study was used concrete by strength class C30/37 with material characteristics at table 1, and steel reinforcement grade B500B and GRFP reinforcement with material characteristics at table 2. Cross-section resistance is determined by the P-M diagram for combination axial force and bending moment. The calculation was considered with the working diagram in figure 2.

Table 1. Material characteristics of concrete.

| Char. value of concrete compressive strength [f_{ck} [MPa]] | Partial factor of reliability \( \gamma_c \) | Design value of concrete compressive strength [f_{cd} [MPa]] | Mean value of modulus of elasticity [E_c [GPa]] | Ultimate compressive strain in the concrete \( \varepsilon_{cu} \) |
|-----------------------------------------------------------|---------------------------------|-------------------------------------------------|-----------------------------|-----------------|
| C30/37                                                   | 30                              | 1.5                                             | 20                          | 32              | 0.0035          |

Table 2. Material characteristics of reinforcement.

| Char. yield strength reinforcement [f_{yk} [MPa]] | Partial factor of reliability \( \gamma_s \) | Design yield strength reinforcement [f_{yd} [MPa]] | Mean value of modulus of elasticity [E_s [GPa]] | Ultimate tensile strain in the reinforcement \( \varepsilon_{uk} \) |
|--------------------------------------------------|---------------------------------|-------------------------------------------------|-----------------------------|-----------------|
| GFRP                                             | 1000                            | 1.25                                            | 800                         | 50              | 0.002           |
| B500B                                            | 500                             | 1.15                                            | 434.8                       | 200             | 0.0025          |

3.2.1 Column element. The study was performed on column elements with cross-section 500×500 mm on different reinforcement ratios. The cross-section was considered as a symmetrically reinforced member. Minimal reinforcement ratio was considered 0.4 %, and maximal reinforcement ratio was considered 4.0 %. The first comparison was focused on compare between element reinforced by GFRP reinforcement with short-term strength, long-term strength, and steel reinforcement with different reinforcement ratio, as shown in figure 3.
Figure 3. Interaction diagrams – Comparison of different reinforcement ratios a) GFRP reinforcement with short-term strength; b) GFRP reinforcement with long-term strength; c) Steel reinforcement.

Compressive resistance is not growing with the reinforcement ratio for elements reinforced by GFRP reinforcement. Tensile resistance for elements reinforced by GFRP reinforcement with short-term increases twice as much as steel reinforcement. On the other side, tensile resistance for elements
reinforced by GFRP with long-term stress is twice lower as much as steel reinforcement. For Steel reinforcement and GFRP reinforcement with long-term strength, bending resistance increase with increasing compressive force. Therefore, a small compressive axial force is often neglected in the design of elements reinforced by steel reinforcement. Though for the short-term strength of GFRP reinforcement, bending resistance increase with increasing tensile force (Figure 4).

3.2.2 Slab element. Further, the parametric study deals with comparing slab elements with cross-section 1000×250 mm on different reinforcement ratios. The cross-section was considered as a symmetrically reinforced member. Minimal reinforcement ratio was considered 0.4 %, and maximal reinforcement ratio was considered 4.0 %. The first comparison was focused on comparing between elements reinforced by GFRP reinforcement with short-term stress, long-term stress, and steel reinforcement with different reinforcement ratio, as shown in figure 5.
Figure 5. Interaction diagrams – Comparison of reinforcement ratio a) GFRP reinforcement with short-term strength; b) GFRP reinforcement with long-term strength; c) Steel reinforcement.

Behaviour interaction diagrams of slab elements are the same as the interaction diagram of column elements. Compressive resistance is not growing with the reinforcement ratio for elements reinforced by GFRP reinforcement because of neglecting effect of GFRP reinforcement in compression. Tensile resistance for elements reinforced by GFRP reinforcement with short-term increases twice as much as steel reinforcement. On the other side, tensile resistance for elements reinforced by GFRP with long-term stress is twice lower as much as steel reinforcement. For Steel reinforcement and GFRP reinforcement with long-term strength, bending resistance increase with increasing force. A slight axial
force is usually neglected in the design of elements reinforced by steel reinforcement. Though for the short-term strength of GFRP reinforcement, bending resistance increase with increasing tensile force (Figure 6).

![Bending Moment vs Axial Force](image.png)

**Figure 6.** Interaction diagram – Comparison of reinforcement ratio

### 3.2.3 Comparison columns and slab elements

The study deals with comparison columns and slab elements. Cross-section areas for concrete, steel, and GFRP reinforcement are the same for both elements. Comparison was performed on three different reinforcement ratios: 0.4, 2.0 and 4.0 %. The interaction diagrams are presented in figure 7, 8 and 9.

Compressive and tensile resistance are the same for column and slab element. However, bending resistance is significantly lower for slab elements than column elements. It is caused by smaller lever arm of the slab cross-section.

According to the study, element reinforced by steel reinforcement has higher compression resistance and bending resistance. The short-term strength of elements reinforced by GFRP reinforcement showed higher tensile resistance. Whereas compression behaviour of GFRP reinforcement is not known, it needs to be verified by experimental study.
Figure 7. Interaction diagram – 0.4 % reinforcement ratio
a) column element 500×500mm
b) slab element 1000×250mm

Figure 8. Interaction diagram - 2.0 % reinforcement ratio
a) column element 500×500mm
b) slab element 1000×250mm

Figure 9. Interaction diagram – 4.0 % reinforcement ratio
a) column element 500×500mm
b) slab element 1000×250mm
4. Conclusion

From the parametric study where observed these facts:

- Tensile and bending resistance is lowest at element reinforced by GFRP reinforcement with long-term strength.
- Tensile resistance is higher at elements reinforced by GFRP reinforcement with short-term strength. Bending resistance is relatively lower at short-term strength of elements reinforced by GFRP reinforcement than elements reinforced by steel reinforcement.
- For Steel reinforcement and GFRP reinforcement with long-term strength, bending resistance increase with increasing compressive force. Therefore, a small compressive axial force is often neglected in the design of elements reinforced by steel reinforcement. On the other side for the short-term strength of GFRP reinforcement, bending resistance increase with increasing tensile force.
- Column element has higher bending resistance than slab element, which is caused by the smaller lever arm of internal forces to the centre of gravity of the element. Tensile and compressive resistance is the same at both elements.
- The compressive strength of GFRP could increase compressive resistance and bending resistance. To confirm this presumption, need to be performed the experimental study.

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