Analysis of flexural strength of beam elements reinforced with GFRP bars

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Abstract. The durability of reinforced concrete structures is associated with the strength of both concrete and reinforcement against aggressive environmental factors. Once a crack or local damage to the cover occur in the structure, traditional methods of protecting the reinforcement are no longer functional and the sensitive steel reinforcement is exposed to corrosion and deterioration. Therefore, a composite reinforcement made with fibre-reinforced polymer (FRP) can be a suitable alternative to the traditional reinforcing steel due to its mechanical and physical properties - high corrosion resistance, high tensile strength, electrical and electromagnetic neutrality. The FRP reinforcement is made of continuous fibres immersed in a polymeric resin. The function of the fibres is to provide adequate strength and stiffness of the composite. Whereas the resin is responsible for bonding the fibres with an appropriate distance between them, protecting their surface against damage and transferring stresses to them. For the purposes of this paper, an analysis of the flexural strength of concrete elements reinforced with FRP bars with varying reinforcement ratios was conducted. The tests were performed on six beam elements reinforced with glass fibre-reinforced polymer (GFRP) bars. The beams with dimensions of 0.15x0.2x2.5 m were subjected to 4-point bending. This study aimed to assess the influence of the reinforcement ratio on the flexural strength of concrete beams reinforced with composite bars and to verify the failure mechanisms against the guidelines presented in the standard ACI 440.1R-06. The reinforcement ratio has a significant impact on the failure mechanism and the flexural strength of beam elements reinforced with GFRP bars. An increase in the reinforcement ratio results in an improvement in the flexural strength of the specimen and is likely to change the failure mechanism - from rebar rupture to concrete crushing. The guidelines of ACI 440.1R-06 correctly estimate the flexural strength of the beam elements reinforced with GFRP bars.

1. Introduction

Reinforcing steel corrosion significantly affects the final durability of reinforced concrete structures. Following the trend of sustainability, solutions have been seeking to increase the durability of structures while minimising negative environmental impact [1]. One possible option is to delay the occurrence of steel corrosion using protective layers on the concrete cover. Alternatively, fibre reinforced polymers (FRP) are considered as a promising substitute for reinforcing steel especially in structures exposed to aggressive environments and the effect of electromagnetic fields [2]. The origins of the use of composite materials made of artificial fibres as reinforcing bars in the structural engineering industry date back to the 1980s.
FRP bars are composed of continuous fibres responsible for the strength and stiffness of the composite. They are embedded in a polymeric resin, which is their bonding material. Moreover, it keeps an adequate distance between them, protects the surface of the fibres against damage and transfers stresses to them. There are four main types of FRP bars: carbon, aramid, glass and basalt. The FRP bars are characterized by high strength, low self-weight, ease of handling, low maintenance requirements and high durability even in rather harsh environments [3, 4]. However, the elastic modulus of FRP bars is reduced in comparison to that of steel bars. Thus, despite a relatively high load-bearing capacity of FRP-reinforced concrete structures, they exhibit brittle failure, larger deflections and crack widths compared with steel-reinforced concrete structures [5–7]. The anisotropic behaviour of FRP affects the shear strength, as well as the bond performance of such reinforcement [8]. Given the implementation of these elements in real structures, a need to standardize the design methods for FRP-reinforced structures has emerged. Scientific committees from different countries provided design recommendations and standards [9–14] dedicated especially to this type of reinforcement with regard to its different characteristics.

One of the most commonly used composite rebars are glass fibre reinforced polymers (GFRP) bars mainly due to their relatively low cost combined with good performance. Many investigations were also performed on GFRP reinforced elements, both simply-supported [15, 16] and continuous [17, 18] beams and plates. In the research [19], the flexural behaviour of 12 GFRP-reinforced and 2 steel-reinforced concrete beams made with normal and high-strength concrete was studied. The main parameters were the surface characteristics of GFRP bars, concrete strength, and reinforcement ratio. It was concluded that the behaviour of GFRP-reinforced beams was significantly different from beams reinforced with steel bars regarding cracking behaviour, post-cracking stiffness, deformation, crack width, and failure mode. It was found that the higher the concrete strength and reinforcement ratio was, the smaller deflection and larger number of cracks, and smaller crack widths occurred in GFRP-reinforced beams. The study [17] showed that current codes ACI 440.1R [9] and CSA S806-12 [14] underestimated deflection of continuous beams with GFRP reinforcement for higher load levels. It was suggested the model presented by Habeeb and Ashour [20] showed better agreement to experimental results during the entire loading process.

The failure of the reinforced concrete elements under bending can occur in two possible forms - as a result of crushing the compressed zone of the cross-section or as a result of exceeding the tensile strength of the reinforcement. The main difference between steel and FRP reinforcement is the linearly elastic tensile behaviour of FRP rods throughout the whole range of operation, which results in a sudden and non-signalised failure of the element. According to ACI 440 [9], the failure mechanism is determined by the reinforcement ratio applied. It is assumed that when the reinforcement ratio \( \rho_f \) does not exceed the limit value of balanced reinforcement ratio \( \rho_{fb} \), the failure will occur by rupture of FRP reinforcement (RR). Whereas when reinforcement ratio is over the limit value, the failure by concrete crushing (CC) is expected. In the case of equal to a balanced reinforcement ratio, the rupture of FRP reinforcement occurs simultaneously with the concrete crushing effecting in the failure of the element.

2. Experimental programme

This paper concerns the analysis on flexural strength of GFRP-reinforced concrete beams with steel transverse reinforcement of different reinforcement ratios. The six beams were constructed to verify the analysed issue. Moreover, the compressive and tensile strength of cubic specimens were tested on overall 40 samples. The tests were carried out after 28 days of concrete curing in laboratory conditions.
2.1. Materials
For the research purposes, one traditional concrete mix was adopted, the composition of which is presented in Table 1. The mix is based on Portland fly ash cement (CEM II/B-V 32,5R). The coarse aggregate in the form of gravel was used. The water-to-cement ratio was adopted at the level of approximately 0.45. The water content was adjusted to the aggregate moisture. The investigations assumed development of concrete with compressive strength of approximately 37 MPa. The recipe was developed based on common literature.

| Ingredients            | Composition [kg/m³] |
|------------------------|---------------------|
| Cement CEM II/B-V 32,5R| 380                 |
| Water                  | 170                 |
| Sand 0/2mm             | 650                 |
| Gravel 2/8mm           | 550                 |
| Gravel 8/16mm          | 650                 |

The investigations were performed on elements with deformed reinforcing bars of different diameters that were made with GFRP. The transverse reinforcement was made of steel reinforcing bars of RB400W class. The mean values of the geometrical and mechanical parameters of the rebars are given in Table 2. All data was provided by the reinforcement manufacturer.

| Material | Diameter | Nominal surface cross-section | Relative rib area | Mass nominal | Mean tensile strength fₚ [MPa] | Mean modulus of elasticity Eₘ [GPa] |
|----------|----------|-------------------------------|-------------------|--------------|---------------------------------|-----------------------------------|
|          | d [mm]   | A [cm²]                       | fᵢ [-]           | m [kg/mb]    |                                 |                                   |
| GFRP     | 6        | 0.283                         |                   | 0.052        |                                 |                                   |
|          | 8        | 0.503                         |                   | 0.098        |                                 |                                   |
| Steel    | 8        | 0.503                         | 0.089             | 0.395        | 440                             | 200                               |
|          | 10       | 0.785                         | 0.070             | 0.147        | 950                             | 55                                |
|          | 11       | 0.950                         |                   | 0.181        |                                 |                                   |
|          | 12       | 1.130                         |                   | 0.223        |                                 |                                   |

2.2. Description of beam specimens
For the purpose of this research, six reinforced concrete elements with dimensions of 150x200x2500 mm were made. The beams were reinforced with GFRP bars. Each element has a different reinforcement ratio. Reinforcement ratio was calculated with equation 1.

\[ \rho_f = \frac{A_f}{b \cdot d} \] (1)

Furthermore, the additional reinforcement used for installation purposes located in the top part of the beam was assumed to be two GFRP bars with a diameter of 6 mm. The transverse reinforcement in the form of single cut steel stirrups of 8 mm bars was adopted at a spacing of 150 mm. The cover thickness was set at 20 mm. The cross-sections of each beam are shown in Figure 1b. The details of the transverse reinforcement arrangement along with the beam specimen and schematic diagram of the experimental set-up are shown in Figure 1a. The beam reinforcement was designed so that all failure mechanisms may be observed.
The concrete was assumed to exhibit a compressive strength of at least 37 MPa. The detailed data concerning individual elements and average values of strength parameters – the compressive and splitting tensile strength of the concrete batch from which the elements was constructed are presented in Table 3. The strength parameters were specified on cubic specimens of dimensions 150x150x150 mm.

| Element type | Reinforcement cross-sectional area $A_t$ [cm$^2$] | Reinforcement ratio $\rho_f$ [%] | Mean cube compressive strength $f_{cc}$ [MPa] | Mean splitting tensile strength $f_{ctm}$ [MPa] |
|--------------|-------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| B1 2#8      | 1.006                                          | 0.40                            | 38.01                           | 3.07                            |
| B2 2#6+1#8  | 1.289                                          | 0.51                            | 37.01                           | 2.76                            |
| B3 3#8      | 1.509                                          | 0.60                            | 37.89                           | 2.92                            |
| B4 2#10     | 1.570                                          | 0.63                            | 35.71                           |                                  |
| B5 2#11     | 1.900                                          | 0.76                            | 36.31                           | 2.54                            |
| B6 2#12     | 2.260                                          | 0.91                            | 41.10                           | 2.64                            |

* Beam designation: the symbol and number of beam element followed by the number of GFRP bars and their diameters

Figure 1. The schematic view of tested elements: (a) longitudinal section, (b) cross-sections of all beams
2.3. Test setup and experimental procedure
The beam samples were 2500 mm long with a clear span of 2000 m simply supported – one pin support and one roller support. All beam specimens were tested under four-point bending through a spreader beam of 800 mm long span. Figure 1a shows the schematic view of an element and Figure 2 pictures the actual test setup during the flexure procedure. The elements were statically loaded until the point of failure, and the obtained value of the ultimate force was used to analyse the problem presented in the paper.

![Figure 2. The arrangement of the test setup](image)

2.4. Analysis procedure
The procedures for determining the flexural strength of elements reinforced with FRP bars are based on the guidelines for steel-reinforced concrete structures. When designing FRP-reinforced elements, the linear relationship between strain and stress shall be taken into account and an adequate reserve of the element's capacity should be provided by applying higher safety factors than in traditionally reinforced beams. The most conservative safety factor is strength reduction factor $\phi$ that depends on the reinforcement ratio and ranges from 0.55 to 0.65.

The flexural strength according to ACI 440 [9] is determined based on the balanced reinforcement ratio. It is calculated from equation (2).

$$\rho_{fb} = 0.85 \beta_1 \frac{f'_c f_{fu}}{f_{fu} E_f \varepsilon_{cu}}$$

Where $\beta_1$, $f'_c$, $f_{fu}$, $E_f$, and $\varepsilon_{cu}$ is respectively a factor dependent on compressive strength of concrete, a specified compressive strength of concrete, a design tensile strength of FRP, a design modulus of elasticity of FRP and an ultimate strain in concrete. According to ACI 440 [9], the ultimate strain in concrete is equal to 0.3%. Subsequently, based on the value of the reinforcement ratio, the nominal flexural strength – $M_n$ – was determined. If the element was designed for a failure by FRP rupture $\rho_f < \rho_{fb}$, a minimum amount of reinforcement should be provided to prevent failure upon concrete cracking.

3. Results and discussions
For the purpose of this article, a series of tests were conducted on beam and cube elements. The results of the compressive strength and splitting tensile strength tests specified on the cubes are presented in Table 3. The average compressive strength of concrete was 37.67 MPa and splitting tensile strength 2.79 MPa.

Table 4 compares the values of the applied reinforcement ratio to the calculated balanced reinforcement ratio. On this basis, the predicted failure mechanism of the flexural beam element was determined. Beams B4 – B6 were designed so that the reinforcement ratio exceeded the balanced reinforcement ratio, beams B1 – B3 had a reinforcement ratio lower than this value. However, beams B3 and B4 had a value close to the limit. The balanced reinforcement ratio varied between beams, due
to differences in the average compressive strength of the concrete from which the component was made. The test programme was designed to enable observation of the influence of the reinforcement ratio on the failure mechanism and flexural strength of GFRP-reinforced concrete elements. The results of experimental studies are presented in Table 5 together with the observed failure mechanism and calculated nominal values of flexural strength, which are then compared with the test results. In Tables 4 and 5, abbreviated names of failure mechanisms were used. In the case of both mechanisms occur simultaneously, the situation is called ‘RR/CC’ in the tables. In Figure 3 both experimental and nominal flexural strength in relation to reinforcement ratio is shown.

**Table 4.** Comparison of the reinforcement ratio with the balanced reinforcement ratio – predicted failure mechanism

| Element type | Reinforcement ratio | Balanced reinforcement ratio | Predicted failure mechanism |
|--------------|---------------------|-----------------------------|----------------------------|
|              | $\rho_f$ [%]        | $\rho_b$ [%]                |                            |
| B1 2#8       | 0.40                | 0.63                        | RR                         |
| B2 2#6+1#8   | 0.51                | 0.61                        | RR                         |
| B3 3#8       | 0.60                | 0.63                        | RR/CC                      |
| B4 2#10      | 0.63                | 0.59                        | RR/CC                      |
| B5 2#11      | 0.76                | 0.60                        | CC                         |
| B6 2#12      | 0.91                | 0.68                        | CC                         |

**Table 5.** Test results compared to calculated nominal values

| Element type | Experimental load | Experimental flexural strength | Nominal flexural strength | Ratio  | Failure mechanism |
|--------------|-------------------|-------------------------------|---------------------------|--------|-------------------|
|              | $P_{exp}$ [kN]    | $M_{exp}$ [kNm]               | $M_n$ [kNm]               | $M_{exp}/M_n$ |                  |
| B1 2#8       | 55.18             | 13.50                         | 12.52                     | 1.08    | RR                |
| B2 2#6+1#8   | 56.37             | 16.91                         | 16.01                     | 1.06    | RR                |
| B3 3#8       | 59.48             | 17.84                         | 18.73                     | 0.95    | RR/CC             |
| B4 2#10      | 66.00             | 19.80                         | 17.50                     | 1.13    | CC                |
| B5 2#11      | 69.19             | 20.75                         | 19.02                     | 1.09    | CC                |
| B6 2#12      | 83.62             | 25.08                         | 21.86                     | 1.15    | CC                |
Figure 3. The flexural strength in relation to the reinforcement ratio

The experimental results of flexural strength increase with an increasing reinforcement ratio. The flexural strength experimental values ranked among 13.50 to 25.08 kNm. The trend-line (Figure 3) leads to a strong linear relation ($R^2=0.967$) with a clearly positive slope. The function and coefficient of determination were developed in the statistical program. The relation is commonly known for steel-reinforced concrete structures as well as FRP-reinforced. The nominal flexural strength calculated according to ACI 440 [9] exhibit in most cases inferior values compared to those obtained in experimental tests. The only value greater than experimental was noted in the case of the element B3 3#8. The Mn values ranged from 12.52 to 21.86 kNm, that is on average 7% less in comparison to experimental ones. The ACI standard provides conservative flexural strength values which are further decreased by safety factors.

On the contrary, the failure mechanism was accurately predicted by the norm. In the case of elements with overestimated reinforcement ratios (when compared to balanced values), the failure resulted from concrete crushing. The beams with a lower amount of reinforcement (B1 – B2) were destructed through FRP rupture. A simultaneous occurrence of both failure mechanisms was detected in the beam B3 3#8, the reinforcement ratio, in that case, was close to the balanced reinforcement ratio. The photos of the elements after destruction through both mechanisms were presented in Figure 4. The failure mechanism was in every case clear to notice. During the concrete crushing in a compressed area of the section, the bucking of top rebars was noted. In both cases of failure, the deterioration of the concrete cover and excessive cracks were observed within the compressed and tensile zones of the section. However, the concrete cover damage level differed between the beams.
4. Conclusions
The paper discusses the flexural strength analysis of the beam elements with different reinforcement ratios with reference to ACI 440 guidelines. The following preliminary conclusions can be drawn from the results of the experimental studies:

- The reinforcement ratio had a significant impact on the failure mechanism and the flexural strength of bent concrete elements reinforced with GFRP bars.
- An increase in the reinforcement ratio in the studied scope resulted in a clear increase in the section's flexural strength. This increment was of a linear dependence character.
- The ACI standard correctly estimates the values of the balanced reinforcement ratio and adequately determines the failure mechanism of flexural concrete elements reinforced with GFRP bars.
- The nominal flexural strength values determined according to ACI recommendations were, on average, 7% lower than those obtained experimentally. The ACI standard provides conservative flexural strength values which are further decreased by safety factors.
- The studies confirm the previously defined literature relationships.

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