Comparison of Failure Process of Bended Beams Reinforced with Steel Bars and GFRP Bars

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Abstract. The Fibre Reinforced Polymer (FRP) composite rebar has been used in civil engineering structures for several years. It has many characteristics, which not only are equal to those of steel rebar, but significantly surpass them. The composite rebar has high corrosion resistance, electromagnetic neutrality and has much higher tensile strength than steel. Also, because of its low weight and easy processing composite rebar is convenient for shipment and use. Development of architectural concrete technology in past years opens new, interesting perspectives for use of composite rebar. However, implementation of those concretes in structures is often burdened with many issues, especially concerning faulty performance. One of it is rebar’s corrosion, visible on the surface of the element as rusty stains. Even if the structure was properly developed meeting all the requirements for texture, porosity or colour uniformity, and rusty stains can completely destroy the final decorative effect of concrete’s surface. Despite many advantages, the use of composite rebar in reinforced structures creates significant number of new “behaviours” in its different working stages. Structures reinforced with the steel rebar will behave differently than the ones with composite FRP rebar under continuous load, in case of a fire, exposed to aggressive environment or at breaking point. In the latter, significant role plays its linear-elastic behaviour in the whole tensile range till rupture. This means that the FPR rebar does not exhibit plastic deformation and reaches its bearing capacity suddenly without any visible signs. This should be considered during designing stage and included as an additional reduction coefficient. The article presents result of research and analysis of destructive tests performed on concrete beams reinforced with traditional steel rebar and composite rebar made of glass fibre and braided with basaltic (GFRP). Four single-span simply supported beams under static load were tested. Both types of beams were designed to have the same bearing capacity. Beams reinforced with GFRP rebar exhibited much bigger cracking than traditionally reinforced bars. The width of cracks appearing in beams reinforced with GFRP bars was equal or greater than limit values (0.4 mm) even though the ratio of moment of resistance and cracking moment was greater than 3. The composite rebar exhibits many significant advantages over steel rebar, but its rather low Young’s modulus comparing to steel causes exceeded deflection and cracking of bended concrete elements.

1. Introduction

Fibre reinforced polymer (FRP) is being used in the civil engineering structures for over 20 years. The composite bars are mostly resistant to chemical aggression, excluding the glass fibre, which have limited resistance to alkali [2]. Some studies confirm the resistance to chloride corrosion of composite rebar [8]. The FRP rebar has much higher tensile strength and magnetic neutrality, is lightweight and easily cut.
making it simple for shipment and processing. The confirmation of above is visible in existing bridge structures, where the working life of concrete slabs is estimated to 25 years for slabs reinforced with steel and at least 75 years for slabs reinforced with FRP bars [4]. Conducted research showed that in tropical conditions platforms reinforced with FPR bars did not deteriorate [5, 6]. Maintenance of Mondial House in London (built in 1974) showed that after 25 years the structure of slab elements reinforced with FRP bars was intact, [7].

Currently there are four different types of composite rebar that are manufactured and utilized, [1]:
- Carbon fibers – CFRP (carbon-fiber-reinforced-polymer),
- Aramid fibers – AFRP (aramid-fiber-reinforced-polymer),
- Glass fibers - GFRP (glass-fiber-reinforced-polymer),
- Basalt fibers - BFRP (basalt-fiber-reinforced-polymer).

The composite bars are made in pultrusion process in which resin impregnated fibers are pulled through heated stationary die where they undergo polymerization. The bar cross-section contains thousands of tiny fibers arranged along the bar’s length. The fibers provide the strength and stiffness of the composite. The resin is used to glue the fibers together, maintain proper distance between them, protect from surface damages and transfer the stress. To maintain proper interaction between bars and concrete, similarly as in steel rebar, the bars are ribbed or covered in a special topping to increase the adhesiveness, [3].

2. Properties of composite rebar
The FRP rebar has many advantageous characteristics over the steel rebar. The comparison of properties and characteristics of composite and steel rebar used in the research is shown in Table 1.

In structure designing use of the FRP bars imposes consideration of its linear-elastic deformation during the whole range of tension up till the rupture. This means that the bars do not exhibit plastic deformation and the capacity loss is sudden and not preceded by any signs. This development is unbeneficial and dangerous and should be taken into consideration during designing phase by including additional reduction coefficients [1]. Unfortunately, currently there are no Polish technical standards that provide principles for designing the elements reinforced with composite fibers. The calculations are mostly based on the American standards and instructions.

The designing process should also take into consideration the differences between the compressive and tensile strength of composite and steel rebar. The composite bars are an anisotropic material. The properties of FRP bars in the longitudinal direction depend on the mechanical properties of fibers, whereas transverse properties and shear resistance depend on the resin [3]. The compressive strength of FPR bars, depending on the type of fibers, comprise of 20% to 70% of tensile strength, thus it is not recommended to implement them in the compression zone of the concrete [1].

From the point of view of the contractor the weight of the rebar is one of the most important characteristics. With the same capacity, the weight of composite rebar is three times lower than the A-III steel. Increased elasticity of the fibre materials also allows for shipment in coils to the site, where it is not required to straighten them because they return to their starting shape once unfolded. This allows for easy shipment both from the warehouse to the construction site and from the laydown area to the actual place of use. No limitations on the length of the coils also reduce the amount of cutting waste. The composite rebar is easier to cut even with hand tools. Due to its low weight the use of crane is not required reducing the overall costs of the construction.
Table 1. Comparison of the properties of steel and composite rebar [1,3,9,10]

| Characteristic               | Unit       | Steel rebar A-IIIN, B500A | GFRP rebar |
|-----------------------------|------------|---------------------------|------------|
| Yield point/tensile strength* | [MPa]      | 500/550                   | 1569       |
| Compressive strength        | [MPa]      | 500                       | Not determined |
| Shear strength              | [MPa]      | 289                       | 194.1      |
| Elastic modulus             | [GPa]      | 210                       | 60         |
| Density                     | [kg/m³]    | 7850                      | 2037       |
| Corrosion resistance        | -          | Corrodes                  | Resistant to corrosion** |
| Thermal conductivity        | -          | Conducts                  | Does not conduct |
| Electric conductivity       | -          | Conducts                  | Does not conduct |
| Isotropy                    | -          | Yes                       | No – low strength crosswise |
| Available diameter          | mm         | 6-80                      | 4-30       |
| Available length            | mm         | Bars up to 15m, coils – no limits*** | No limits**** |
| Processing – cutting        |            | Hard                      | Easy       |
| Processing – bending        |            | Possible on site          | Only during production |
| Price                       |            | Low                       | High       |

*Due to plastic reserves in GFRP rebar the yield point of steel corresponds to tensile strength of the composite material  
**GFRP rebar – limited resistance to alkali  
***Use of steel bars in coils require time-consuming straightening on site with dedicated equipment – in practice the steel rebar in coils is rarely used outside the rebar manufactures and prefabrication sites.  
****Composite rebar have high elasticity – the bars in coils do not have to be straightened.

3. Experimental tests
The aim of performed tests was to compare the development of the failure process of beams reinforced with the composite and steel rebar. Obtained results were used to verify the theoretical calculations. Study focused on the failure process mechanism and comparison of deflection of the elements.

3.1. Research model
Four single-span simply supported beams under static load were tested. The geometry and rebar schematics of the beams (200 x 100 x 2000 mm) are shown in Fig 1. The top bars (Φ8 mm) as well as stirrups (Φ6.5 mm) were made of B500A steel. The bottom bars were made from the steel in first two beams and GFRP in the other two, all of them with 6.5 mm diameter as shown in Table 1. The span between the supports was set to 1500 mm. The load was applied to the beams through steel traverse as two concentrated forces with distance of 500 mm from support axis. Proposed static diagram (Fig. 4) allowed isolating the area from the shear forces.
3.2. Measurements on tested beams

![Rebar schematics of tested beams](image1)

**Figure 1.** Rebar schematics of tested beams

![Rebar frame of beams reinforced with GFRP and steel bars](image2)

**Figure 2.** (a) Rebar frame of beams reinforced with GFRP and steel bars  
(b) Rebar frame in the formwork during casting

The study included measurement of vertical deflections in the middle of the span and the stress values in compression and tension zones. The strain of concrete was measured using a set of 10 tensometers (5 measuring and 5 compensating) T1-T5 with 50 mm length and the resistance of 289±1Ω. The strain of steel and GFRP bars was measured using a set of 4 tensometers (2 measuring and 2 compensating) with
20 mm length and resistance of 120±1 Ω. The measuring tensometers were placed between the applied loads in 4 different sections showed in Figure 3.

![Figure 3. Tensometers’ placement on the beam](image)

![Figure 4. Prepared research model](image)
4. Results

Results of the study presented below in the Figure show the stress increment due to application of load. The graphs show comparison of stresses measured in the same section in two different beams. Figure 5a shows values of stresses measured on the top surface of beams’ compression zone at the location of cracked section (tensometer 1). In both cases the increment of stresses was clearly higher after the appearance of the first cracks. In the beam reinforced with the composite rebar (top curve) first, sudden change of the curve’s development at the load of 13 kN was caused by the appearance of the first crack and resulted in increase of deflection. The appearance of crack caused also sudden increase of compressive stresses. Consecutive local disturbances of curve’s development mostly visible as temporary decrease of the applied load were caused by rapid opening of successive cracks. Appearance of each consecutive crack corresponds with the abrupt local increase of stresses in rebar and concrete. In case of the beam reinforced with steel rebar (bottom curve) the increase of the stresses after appearance of cracks was also linear, with lower slope (slower) than in case of GFRP rebar. This occurred until depletion of capacity reserves of the steel. The moment the limit stresses were reached in rebar the yielding of steel occurred which caused rapid increase of compressive stresses in concrete and consequently failure of the beam.

The development of stresses in the section between two consecutive cracks is similar to the one at crack location, however the values are significantly lower (Figure 5b). Appearance of consecutive cracks influences the stress values measured at the previous crack locations. There are clearly visible changes in stress development in the beam reinforced with GFRP caused by rapid and strong cracking.

Figure 6a shows measurements from tensometers installed directly on the bottom bars of tested beam. The graphs show linear-elastic work of the beam up until the moment of cracking. After reaching the limit of concrete’s tensile strength, the rapid increase of the stress in the bars can be seen, especially in beams reinforced with composite rebar.
The level of stresses on the surface of beam reinforced with composite rebar is constant and does not exceed concrete’s tensile strength. In the steel reinforced beam, sudden increase of stress was observed as a result of appearance of another crack and lead to destruction of the tensometer. In the end the beams reinforced with GFRP rebar had lower number of cracks however much deeper and wider from the start (Figure 6a). The comparison of both beams visible in Figure 6b indicates much higher deflection of beam reinforced with the composite rebar. The deflection curve in case of beams with GFRP bars has bigger slope (the deflection increases more quickly) which is caused by lower elastic modulus of the composite comparing to steel (Table 1). Sudden surges of the deflection were observed at the moment of appearance of consecutive cracks. Three different operating stages of beam reinforced with steel rebar can be distinguished by looking at the angle of the deflection curve: operating without cracks, operation with cracks, yielding of steel.

Figure 6. (a) Comparison of stresses in the compression zone at the location of first crack (b) Comparison of deflections of beams reinforced with GFRP and steel bars

Both beams were designed in accordance with the basic methods for calculating the amount of rebar in bended reinforced concrete elements. According to performed calculations the failure should happen due to depletion of the capacity of rebar. However in the case of beams reinforced with composite rebar the failure was caused by exceeding the capacity of compression zone (Figure 8a). This is caused by the
depth of crack penetration that reached ¾ of cross-section’s height thus drastically reduced the height of compression zone. Failure of the beams reinforced with steel rebar progressed in an expected way. The loss of capacity was caused due to yielding of steel rebar (Figure 8b).

Figure 8. (a) Failure of the beam reinforced with GFRP bars (b) Failure of the beam reinforced with steel bars

5. Conclusion

- The use of composite rebar propagates the occurrence of much bigger cracking than use of steel rebar. Observed cracks from the start are deeper and wider.
- Studied beams were designed to reach failure by rupture of the tensile bars. The bearing capacity of beams reinforced with the composite rebar was similar to the beams with steel rebar. Because of capacity depletion of concrete in GFRP reinforced beams, we can suspect that assumed stress pattern in the cross-section at the point of failure was improper.
- Significant formability of the GFRP bars (3-4 times higher than of steel bars) enforces modification in the current models of cross-section stress patterns that are used for dimensioning of rebar. This would allow to fully utilize the capacity of composite bars and concrete.
- The failure of the bended element due to the rupture of composite rebar is sudden. The cracking of the elements reinforced with GFRP has untypical development and can cause issues in the evaluation of element’s state. The cracks in beams reinforced with GFRP from the very start had the same width or were wider than limit width (0.4 mm) even though the ratio of moment of resistance to cracking moment (Mr/Mcr) was over 3.
- Due to the low value of elastic modulus of GFRP rebar bending elements exhibit relatively big deflections.
- Replacing the steel rebar with composite GFRP rebar, due to lack of proper Polish technical standards and instructions should not be done without preceding experimental tests both for ULS and SLS.

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