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# Bond coefficients of beams reinforced with FRP and strengthened with FRC fibres

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## Abstract

There are several reasons why civil and structural engineers may need to use resin matrix continuous fibre (fibre reinforced polymer – FRP) reinforcement in concrete. The unique FRP characteristic, i.e. the fact that it is not susceptible to corrosion, makes its use particularly suitable in various situations. However, due to generally low elastic modulus and poor bond, the use of FRP results in larger crack widths under SLS, especially in the case of beams reinforced with GFRP bars. The work presented herein includes results obtained on 24 beams tested under four-point bending for GFRP beams with plain concrete and FRC. Based on this approach, the existing codes (ACI 380, Eurocode 2, ISIS, CSA etc.) are reviewed and compared, and also modified (adapted), in order to calibrate with the corresponding results. Corrective bond coefficients are introduced as reflection of bond characteristics, and fibre coefficients are used to quantify the effectiveness of FRC.

*Key words: RC Beams, GFRP, CFRP, FRC, "kb" and "k1" values, fibre coefficients, cracks*

# Koeficijenti prionljivosti za grede od vlaknima pojačanog betona armirane FRP armaturom

## Sažetak

Postoji više razloga zbog kojih bi građevinari i konstrukteri trebali koristiti pojačanje betona u vidu kontinuiranog vlaknastog armiranja s matricom od smole (polimera armiranog vlaknima – FRP). Jedinstvena karakteristika FRP-a, tj. otpornost na korozivno djelovanje, čini taj materijal posebno pogodnim za razne namjene. Međutim, zbog općenito niskog modula elastičnosti i lošeg vezivanja, primjena FRP-a dovodi do pojave većih pukotina u graničnom stanju uporabivosti, naročito u slučaju greda armiranih GFRP šipkama. U ovom radu prikazani su i rezultati dobiveni na 24 grede, koje su ispitane savijanjem u četiri točke, za GFRP grede s običnim betonom i FRC-om. Na temelju tog pristupa, postojeće norme se analiziraju (ACI 380, Eurokod 2, ISIS, CSA itd.) i uspoređuju te modificiraju (prilagođavaju) kako bi se provelo usklađivanje s odgovarajućim rezultatima. Uvode se korektivni koeficijenti vezivanja kao odraz karakteristika vezivanja, a koeficijenti vlakana koriste se za kvantificiranje djelotvornosti FRC-a.

*Ključne riječi: B grede, GFRP, CFRP, FRC, vrijednosti "kb" i "k1", koeficijenti vlakana, pukotine*

# 1 Introduction

Corrosion as phenomenon is one of the most common causes of deterioration in reinforced concrete structures. The alkaline environment of concrete normally provides necessary protection to conventional steel reinforcement from the environment by a passive oxide layer that forms on the surface of reinforcement. Nonetheless, when exposed, or when the alkaline environment is neutralised, conventional steel corrodes and leads to spalling of the concrete cover. Codes of practice prescribe thick concrete covers for steel reinforcement, as well as other measures aimed at controlling concrete crack width and reducing permeability. Corrosion occurs also when chloride ions penetrate through concrete into reinforcement and cause breakdown of the protective oxide layer [7]. Deicing salts (parking lots, highway structures, marine structures) are a major factor of the chloride induced corrosion. Current methods for preventing corrosion, such as those relating to permeability or protection of reinforcing bars, are either costly or their long-term effectiveness has not been established.

The use of FRP in concrete for anti-corrosion purposes is expected to find applications in structures in or near marine environments, in or near the ground, in chemical and other industrial plants, in places where good quality concrete cannot be achieved, and in thin structural elements. Nowadays, FRP bars have increasingly become commercially available and are therefore utilized in many countries. A number of studies have recently been made about using FRP to replace conventional steel as flexural reinforcement [1]. There are several reasons why civil and structural engineers may need to use FRP reinforcement in concrete. The primary reason is durability, but other reasons include electromagnetic neutrality (steel reinforcement can interfere with magnetic fields), high strength (high strength of FRP reinforcement can be utilized to reduce congestion of reinforcement in certain applications), high cut ability in temporary applications, and lightweight. Most types of FRP bars exhibit a low elastic modulus and have a relatively poor bond to concrete. Direct yielding effects are larger crack widths and deflection under service load when compared to beams reinforced with conventional steel bars. Additional disadvantages are related to linear elastic behaviour with no yielding zone and long-term durability of FRP bars in concrete environment [2].

Fibres as micro-reinforcement is a concept applicable in various fields. FRC can be defined as concrete containing relatively short, discrete, discontinuous fibres. The fibres tend to bridge the cracks, control crack development and prevent occurrence of large cracks [3]. This feature of fibres tends to cover the yielding effects of low elastic modulus of beams reinforced with FRP, especially GFRP. The purpose of this study is also to determine whether the use of fibres can improve cracking resistance in concrete. Beams reinforced with GFRP bars are more influenced by excessive crack widths and for that purpose three sets of identical beams (in terms of geometry and reinforcement) were tested in order to identify differences when fibres are added (plain concrete vs FRC). The cracking response of specimens was studied so as to clarify improvements that came as a result of fibre reinforcement.

## 2 Experimental works

The reinforced concrete beams consist of twenty-four specimens with various reinforcement, of rectangular cross section, measuring 130 mm in width and 220 mm in height. Each reinforced beam specimen contains two reinforcing bars placed at the bottom in a single layer, and two identical bars (ϕ6 conventional steel) placed as top reinforcement for each specimen (behaviour of FRP bars in compression section is not determined). The cross-section geometry and number of reinforcing bars were chosen so as to represent various reinforcement conditions (insufficient reinforcement, balanced reinforcement, and excessive reinforcement). Specimen geometry and loading conditions can be seen on Figure 1. Concrete mix was prepared with the requested class of concrete C 30/37. An adequate number of specimens were cast during beam casting.  At the same time, another six prisms were cast with plain concrete and FRC.  The FRC used in this investigation contained micro polypropylene fibres with a fibre fraction of 0.063% or 600gr/m$^3$ [4]. Monofilament polypropylene fibres had a tensile strength of 650 Mpa, an elastic modulus of 3.5 GPa, and a length of 12 mm. This dosage of fibres is partly suggested by fibre manufacturer, and it also comes from our tendency to economise the FRC as related to conventional concrete. The test procedure is compliant with guidelines given in EN 14651: 2005, and it involves prismatic specimens measuring 150x150 x 600 mm, and three-point bending process, as presented in Figure 2. The specimens are notched at mid span with a high 25 mm notch.


**Figure 1. Experimental setup for flexure test of notched specimens**

The loading was performed with deformation control. The method allows measurement of force-displacement or force-CMOD (crack mouth opening displacement) relations. One transducer was installed on the specimen at mid-depth directly over supports to measure the corresponding deflection [8]. During the flexure testing, the same rate of the CMOD is maintained throughout the process.

**Table 1. Test specimens**

| Spicement | Reinforcing type | Bar size, metric | Concrete type | Compaction cubic strength, Mpa | Flexure strength, Mpa | Reinforcing ratio ρ, % | Balanced reinforcing ρb, % |
|---|---|---|---|---|---|---|---|
| S1G1 | GFRP | ϕ6 | Plain | 36.6 | 3.96 | 0.22 | 0.50 |
| S2G2 | GFRP | ϕ8 | Plain | 37.1 | 3.53 | 0.40 | 0.45 |
| S3G3 | GFRP | ϕ10 | Plain | 38.1 | 4.19 | 0.63 | 0.35 |
| S1S1 | Steel | ϕ6 | Plain | 36.6 | 3.56 | 0.22 | 1.59 |
| S2S2 | Steel | ϕ8 | Plain | 38.1 | 3.53 | 0.4 | 2.10 |
| S3S3 | Steel | ϕ10 | Plain | 38.1 | 3.62 | 0.63 | 2.99 |
| S1G1F | GFRP | ϕ6 | FRC | 36.6 | 3.37 | 0.22 | 0.50 |
| S2G2F | GFRP | ϕ8 | FRC | 37.1 | 3.47 | 0.40 | 0.45 |
| S3G3F | GFRP | ϕ10 | FRC | 38.1 | 3.45 | 0.63 | 0.35 |

The testing set up for beams was organised in such a way that LVDTs were placed in critical positions for analysing cracks, deflections, and displacements. One LVDT was used to measure the width of the first flexural crack in the beam right under the concentrated force.

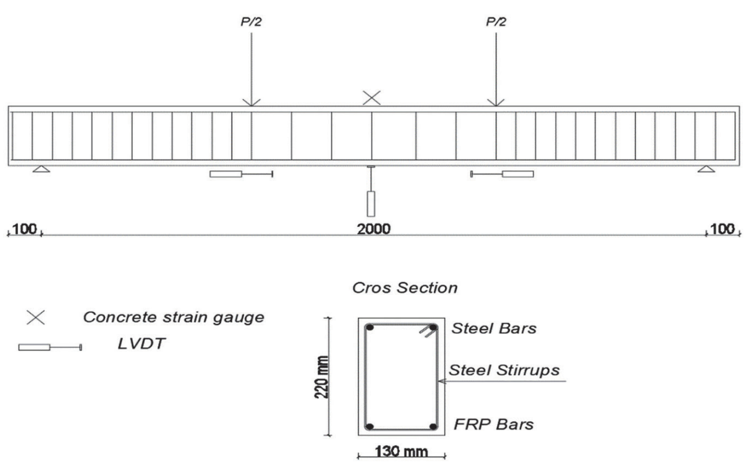


**Figure 2. Beam details, instrumentation, and geometrical parameters of concrete beams**

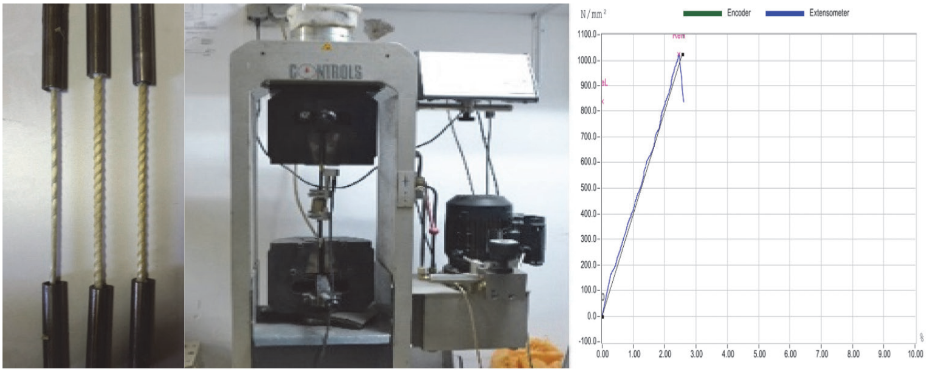


**Figure 3. Specimens, testing, and determination of mechanical properties of GFRP bars**

Mechanical properties of FRP bars were examined based on ASTM D 7205 [9]. The edges of the bars were embedded inside engraved metallic cylinders in order to avoid constriction or shear stress of the FRP bars as shown in Figure 2, [5]. Conventional steel properties were defined according to known parameters based on previous research works for S 500. GFRP (helically grooved) bars were used in this research [10].

**Table 2. Mechanical properties of GFRP bars and conventional bars**

| Bar type | Bar size, metric | Elastic Modulus [Gpa] | Tensile strength [Mpa] | Design tensile strength [Mpa] | Yield strain [%] | Rupture strain [%] |
|---|---|---|---|---|---|---|
| (S1B1) GFRP | ф6 | 50.59 | 1022 | 731.3 | / | 1.2 |
| (S2B2) GFRP | ф8 | 54.3 | 1108.2 | 802.7 | / | 2.34 |
| (S3B3) GFRP | ф10 | 52.08 | 1218.8 | 903.5 | / | 2.72 |
| (S5B1) Steel | ф6 | 200 | 400 | 347.8 | 2 | 10 |
| (S7B2) Steel | ф8 | 200 | 400 | 347.8 | 2 | 10 |
| (S8B3) Steel | ф10 | 200 | 400 | 347.8 | 2 | 10 |

## 3 Different approaches of adhesion coefficients kb, and k1 and introduction of fibre coefficients k5, kfb, kfb'

Symbols kb and k1 denote coefficients that account for the degree of bond between FRP bar and the surrounding concrete. The adhesion coefficient kb refers to ACI 318 Gergely-Lutz equation while k1 is the bond coefficient for crack width calculation in Eurocode 2. An average value of kb has been found to range from 0.60 to 1.72 depending on the type of FRP, manufacturers, fibre types, resign nature, and type of surface treatments, while k1 ranges from 0.8 to 1.6. Some typical kb predicted values for deformed GFRP bars cited in ACI are between 0.8 and 1.80. However, ACI Codes and Manuals suggest that designers assume a value of 1.2 for deformed GFRP bars unless more specific information is available for a particular bar. The ACI Committee 440 modified the Gergely-Lutz equation for the use with concrete members incorporating the effects of different bond and mechanical properties of FRP.

$$w = 2.20 \frac{f_{frp}}{E_f} \cdot \beta \cdot k_b \cdot \sqrt[3]{d_c \cdot A} \tag{1}$$

When the stress is represented as a function of the moment, the Gergely-Lutz equation can be used to plot the moment versus crack width.

$$w = 2.2 \frac{M}{A_{frp} \cdot E_{frp} \cdot j \cdot d} \cdot \frac{h_2}{h_1} \cdot k_b \cdot \sqrt[3]{d_c \cdot A} \tag{2}$$

The pre-cracking behaviour of beams does not correspond to the linearity nature of the Gergely-Lutz equation because the width starts to increase with the moment only at the cracking moment when the crack first forms. A modification to the Gergely-Lutz equation [12] was used to include the pre-cracking behaviour, as a crack does not form immediately with the application of moment but rather when the tensile strength has been reached [6].

$$w = 2.2 \frac{M - M_{cr}}{A_{frp} \cdot E_{frp} \cdot j \cdot d} \cdot \frac{h_2}{h_1} \cdot k_b' \cdot \sqrt[3]{d_c \cdot A} \tag{3}$$

The Eurocode 2 crack width equation is strain-based and can be adopted directly for determining the crack width of FRP RC elements (3). The difference in bond characteristics is implemented through the coefficient $k_1$ and for long terms stress via the parameter kt.

$$w = s_{r,max} \cdot (\varepsilon_{sm} - \varepsilon_{cm}) \tag{4}$$

($\varepsilon_{sm}$-$\varepsilon_{cm}$) is the difference in deformation between bars and concrete over the maximum crack distance.

In this expression, the strain difference can be calculated as for an ordinary concrete. However, a new coefficient needs to be introduced in the crack spacing formula where $k_5$ is the additional factor that accounts for the effects of fibres.

$$s_{r,m} = k_3 c + k_1 k_2 k_4 k_5 \frac{\varnothing}{\rho_{p,eff}} \tag{5}$$

Fibre effect coefficients incorporate the ratio of tensile strength and residual tensile strength where calibration values are obtained through experimental investigation [10]. Also, fibre coefficients $k_{fb}$ and $k_{fb}$' were implemented for Gergely-Lutz and modified Gergely-Lutz equation.

$$w = 2.2 \frac{M}{A_{frp} \cdot E_{frp} \cdot j \cdot d} \cdot \frac{h_2}{h_1} \cdot k_b \cdot k_{fb} \cdot \sqrt[3]{d_c \cdot A} \tag{6}$$

$$w = 2.2 \frac{M - M_{cr}}{A_{frp} \cdot E_{frp} \cdot j \cdot d} \cdot \frac{h_2}{h_1} \cdot k_b' \cdot k_{fb}' \cdot \sqrt[3]{d_c \cdot A} \tag{7}$$

An additional aim of this study is to develop bond models that can accurately simulate the response regarding improvement of crack width for GFRP reinforced concrete beams. ATENA is used as software analyser and, based on experimental results, the corresponding bond models are calibrated. The bond model strives to develop behaviour of reinforcement relating to concrete using the slip (m) versus bond strength relation.

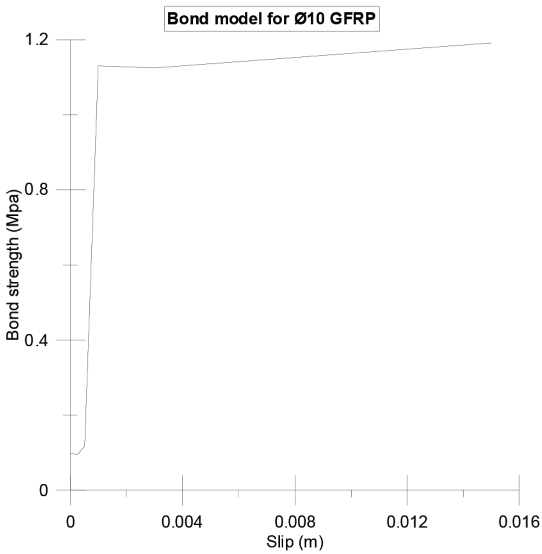


**Figure 4. Bond model - performance function of bond characteristics**

## 4 Test Results and Discussion

Bond coefficients for beams reinforced with steel bars were close to 1, as expected, because the original Gergely-Lutz equation is based on the steel-concrete relation. A reduction in bond coefficient means improvement of bond characteristics of the reinforcing bar in comparison to steel. Bond characteristics are represented with k1 in Eurocode 2, and values larger than 0.8 denote worse bond characteristics related to steel.

Sets with minimum or balanced GFRP reinforcement (S1B1 and S2B2) revealed inferior bond characteristics related to steel, while excessively (over-) reinforced sets (S2B2) exhibited relatively similar bond characteristics.

The corresponding values of bond coefficients in different phases of loading are shown in Figure 4, where the difference in the bond coefficient of the modified Gergely-Lutz can clearly be seen. The approximation happens only in the pre-cracking phase, while the difference from reference values can be observed in the following phases. An increase in fibre ratio affects the pre-cracking behaviour, but the ratio taken for this experiment did not archive the nominal fibre content in order to influence the post-cracking behaviour (3).

**Table 3. Calculated bond coefficients**

| | | SET | S1B1 | S2B2 | S3B3 | S5B1 | S7B2 | S8B3 |
|---|---|---|---|---|---|---|---|---|
| Bar diameter [mm] | | 6 | 8 | 10 | 6 | 8 | 10 | |
| Bar type | | GFRP | GFRP | GFRP | Conventional | Conventional | Conventional | |
| Corrective bond coefficients | "SLS" State | k1 | 0.65 | 1.8 | 0.7 | 1.1 | 0.7 | 1 |
| | | kb | 0.95 | 1.5 | 0.85 | 1.3 | 0.85 | 1 |
| | | kb' | N/C | N/C | 1.2 | N/C | 1.25 | 1.4 |
| | (M/Mu - 50%) | k1 | 1.1 | 1.6 | 0.8 | N/C | 0.95 | 1 |
| | | kb | 1.4 | 1.6 | 1 | N/C | 0.95 | 0.9 |
| | | kb' | 3.5 | 2.7 | 1.2 | 0.8 | 1.2 | 1.6 |
| | (M/Mu - 75%) | k1 | 0.95 | 1.6 | 1.1 | N/C | 0.8 | 0.9 |
| | | kb | 1.45 | 2.4 | 0.95 | N/A | 0.8 | 0.95 |
| | | kb' | 2.4 | 3.3 | 1.15 | 0.6 | 1.3 | 1.5 |

**Note; N/C-Not corresponded while $M/M_u$ is percentage of load*

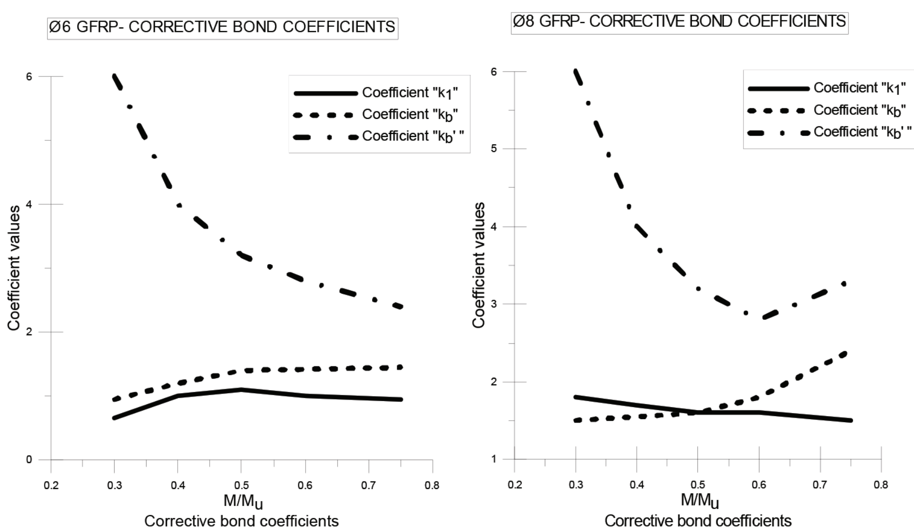


**Figure 5. Corrective bond coefficients versus M/Mu**

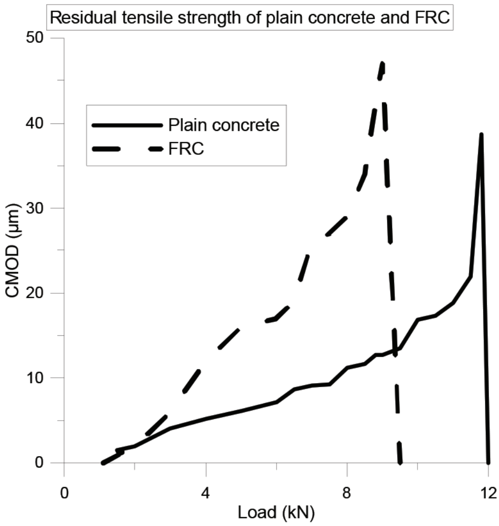


**Figure 6. Effects of fibres in relation to Load-CMOD**

Ductile behaviour is not influenced by adding a small fraction of fibres. On the contrary, some parameters such as the volume fraction, fibre length, and modulus of elasticity, tend to improve brittle failure. Fibres on the fracture surface did not bridge the cracks and behaved in an inactive manner, like voids or errors in concrete matrix.

**Table 4. Calculated fibre coefficients**

| | | **"SLS" State** | | | **(M/Mu - 50%)** | | | **(M/Mu - 75%)** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Fibre coefficients** | | | **Fibre coefficients** | | | **Fibre coefficients** | | |
| SET | Bar type | k5 | kfb | kfb' | k5 | kfb | kfb' | k5 | kfb | kfb' |
| S1B1 | Ø6 GFRP-F | 1.2 | 1.1 | 1 | 0.75 | 0.85 | 0.75 | 0.75 | 0.9 | 0.85 |
| S2B2 | Ø8 GFRP-F | 0.9 | 0.95 | 0.85 | 0.95 | 1.2 | 1.15 | 1 | 0.9 | 0.9 |
| S3B3 | Ø10 GFRP-F | 1.8 | 1.4 | 1.7 | 1.55 | 1.35 | 1.35 | 1.2 | 1.5 | 1.5 |

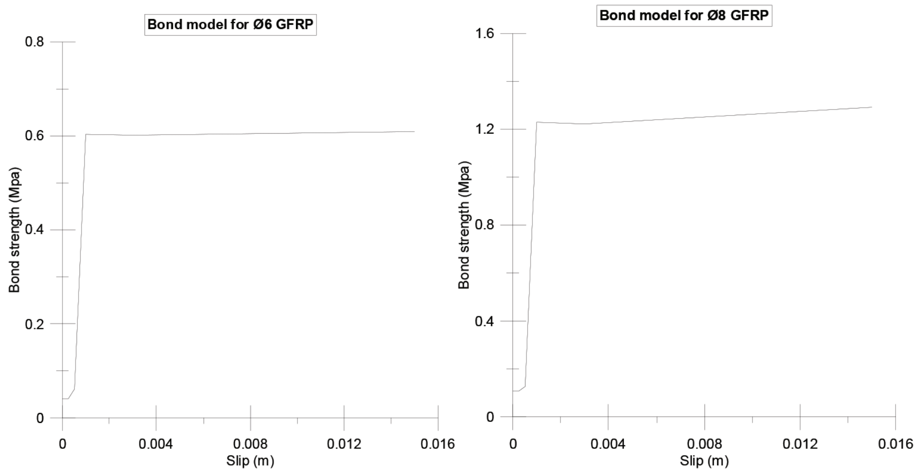


**Figure 7. Bond model- performance function of bond characteristics**

Based on experimental results, the corresponding bond models were developed as a function of bond strength and slip.

# 5 Conclusions

The cracking behaviour of plain and polypropylene FRC beams with GFRP and reference conventional steel was analysed. The following conclusions can be drawn from the experimental investigation results:
Beams with balanced reinforcement and especially over-reinforced (excessively reinforced) GFRP beams (7 to 10% deviation) tend to approximate with reference values of bond coefficients while beams with minimum reinforcement have shown inferior bond characteristics.
Analytical approach for crack calculation has shown adaptation through bond coefficients, except for the modified Gergely-Lutz equation that has shown compliance in the pre-cracking phase only.
Through fibre coefficients, an attempt was made to incorporate the effects of fibres with variation of residual tensile strength as yield effect.
The addition of small quantity of polypropylene fibres does have a contrary effect as related to the pre-yield cracking behaviour.
The effect of fibres can be obtained in the final stage of bearing capacity with symbolic influence (1%-S1G1F, 6%-S2G2F, 1.5%-S3G3F) as related to reference beams without fibres.
This investigation was conducted to determine the measured values of kb, and this experiment showed that there is a significant difference between the values deter-

mined according to different standards and the measured real values. The authors therefore suggest that the design be more based on measured values than on theoretical ones. Otherwise, to accurately determine the behaviour of bars in terms of bond coefficient, additional research should be conducted in the future, involving a large number of measured values.

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