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Bond Coefficient k_b of Concrete Beams Reinforced with GFRP, CFRP, and Steel Bars

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Abstract

There are several reasons why civil and structural engineers should use Fiber Reinforced Polymer bars in concrete. The primary reason is durability, and other relevant parameters, high strength and, lightweight. Non-corrosive attributes make their use particularly suitable in different situations. Due to low elastic modulus and poor bonding, the use of Fiber Reinforced Polymer results in larger crack widths under serviceability limit state especially beams reinforced with glass fiber bars. The study purpose of this paper is to investigate the k_b values. The methodology of this paper is comparing the analytical and experimental results. The investigation included 12 beams, using the four-point load test. The geometrical parameters of tested beams with dimensions: 130×220×2200 mm, reinforced with different diameters, helically-grooved glass fiber bars, and sand-coated carbon fiber bars. The measured cracks were used to assess the current k_b values recommended in the design codes and guides. The findings did not support the use of the same k_b value for different bars because, in addition to the type of bar, the value of k_b is also affected by the type of surface and the diameter of the bar. What is observed based on results shows that CFRP bars have a more constant value depending on the diameter, while GFRP bars have large value changes depending on the diameter.

Keywords: RC Beams; Bars; k_b Values; Deflections; Cracks.

1. Introduction

Corrosion is one of the most common causes of deterioration in reinforced concrete structures. The alkaline environment of concrete normally provides the 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 neutralized, conventional steel corrodes lead to an increase in the volume and destruction of the concrete cover. Codes of practice prescribe the thickness of the concrete cover to the steel reinforcement in decreasing the crack widths and reduce permeability. Corrosion occurs also when chloride ions penetrate through the concrete into reinforcement level and cause a breakdown of the protective oxide layer. Deicing salts (parking, highway structures, and marine structures) are the major factors of chloride-induced corrosion. Current methods for preventing corrosion like permeability or protection of reinforcing bar, are costly or undetermined in long-term effectiveness. The use of Fiber Reinforced Polymer (FRP) in concrete for corrosion protection 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 are more commercially available and used in many countries. Many recent studies have been conducted using FRP as a substitution of conventional steel as flexural reinforcement.

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There are several reasons why civil and structural engineers should use FRP reinforcement in concrete. The primary reason is durability, but other reasons include electromagnetic neutrality (Steel reinforcement can interfere with magnetic), high strength (the high strength of FRP reinforcement can be used to reduce congestion of reinforcement in certain applications), high cut-ability in temporary applications, and lightweight. Direct yielding effects are larger crack widths and deflections under service loads compared with beams reinforced with conventional steel bars. Additional disadvantages are related to linear elastic behavior with no yielding zones and long-term durability of FRP bars in the concrete environments [1-4]. Most types of FRP bars with low elastic modulus and relatively poor bond to concrete directly indicate the behavior of structural elements [5-7]. Since cracks are parameters from which the bonding mechanism between FRP bars and concrete is evaluated, and knowing that the modulus of elasticity of these bars is much smaller than steel bars (especially GFRP bars), the evaluation of k_b parameter will be done in Serviceability Limit State. This fact is considered in FRP design code and guides through the so-called bond coefficient (k_b) [8] and [9]. Also, the bond between concrete and FRP bars depends on many factors like bar surface, bar diameter, concrete class, etc. It was noticed that there has been a tendency for FRP bars of larger diameter to show lower bond strength [10-12]. Since all these parameters are expected to have an impact on the bond coefficient, this article presents research for the determination of k_b taking into account all these factors, such as the type of bar surface, bar diameter, concrete class, etc. Also, in this paper is made a comparison of experimentally achieve values with different design standards recommended values

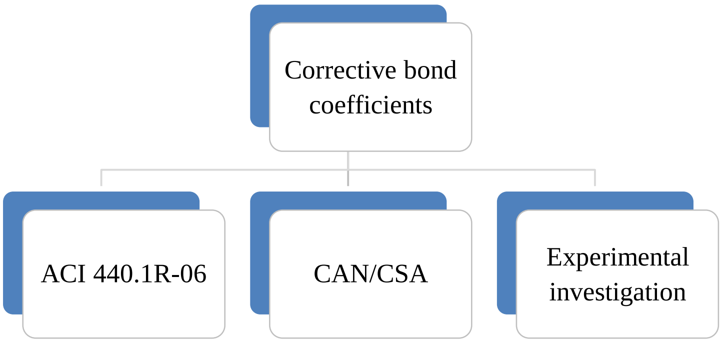

Figure 1. Flowchart of evaluating bond coefficients

2. Experimental Procedure

The process of investigation continued in the laboratory, where the concrete beams were cast under laboratory conditions, left for 28 days, and then put into the testing machine for examinations of the requested parameters. The beams were simply supported and subjected to a four-point bending load. During the examination, the values for each parameter were recorded, like displacement versus time-load applications, crack width, deflections, and maximum load. After obtaining data, experimental and analytical data were compared and analyzed with different codes. Besides the main prescribed codes, other approaches were also conducted for deflection calculations and crack evaluation [13-15]. The beams of reinforced concrete consist of fifteen specimens with various reinforcement and rectangular cross-sections, with a width of 130 mm and a height of 220 mm. Each reinforced beam specimen contains two reinforcing bars placed on a single layer placed in the bottom and two identical bars (ϕ6 conventional steel) were placed as top reinforcement for each specimen (undetermined the behavior of FRP bars in compression section). The cross-section geometry and several of reinforcing bars were chosen to represent various reinforcement conditions (under reinforcement, balanced, and over reinforcement) [16-18]. The specimen geometry and loading conditions are presented in Figure 2. The concrete mix design was prepared with the requested class of concrete C 30/37. The test procedure was made using prismatic specimens with dimensions 150×150×600 mm, testing in three-point bending, presented in Figure 3.

Figure 2. Preparing beams and sampling [23]

One transducer is installed on the specimen at mid-depth directly over supports to measure the corresponding deflection. During the flexure testing, the same rate of the deflection control is maintained during the process.

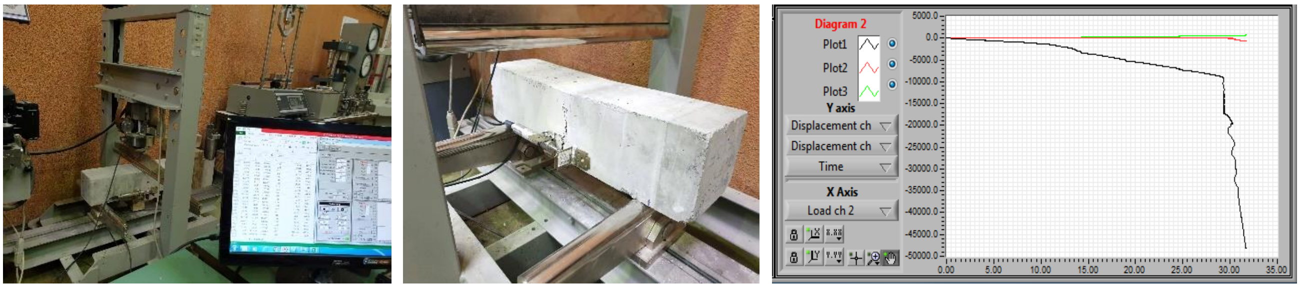

Figure 3. Experimental setups for flexure test of specimens

The compressive strength, modulus of elasticity and other mechanical properties of concrete were determinate by testing the standard cylinder, cubic specimens and, prismatic specimens where the results are shown in Table 1.

Table 1. Test specimen's parameters

Specimen	Reinforcing type	Bar size, metric	Compaction cubic strength, MPa	Flexure strength, MPa	Reinforcing ratio ρ, %
S1G1	GFRP	ϕ6	36.6	3.96	0.22
S2G2	GFRP	ϕ8	37.1	3.53	0.40
S3G3	GFRP	ϕ10	38.1	4.19	0.63
S1S1	Steel	ϕ6	36.6	3.56	0.22
S2S2	Steel	ϕ8	38.1	3.53	0.4
S3S3	Steel	ϕ10	38.1	3.62	0.63
S1C1	CFRP	ϕ8	36.6	3.37	0.40
S2C2	CFRP	ϕ10	37.1	3.47	0.64

Beam testing was done with Linear Variable Differential Transformers placed in critical positions to measure cracks and deflections. The devices for measuring cracks are placed in the same direction with concentrated forces because the first and the largest cracks width are expected to appear exactly under these two forces.

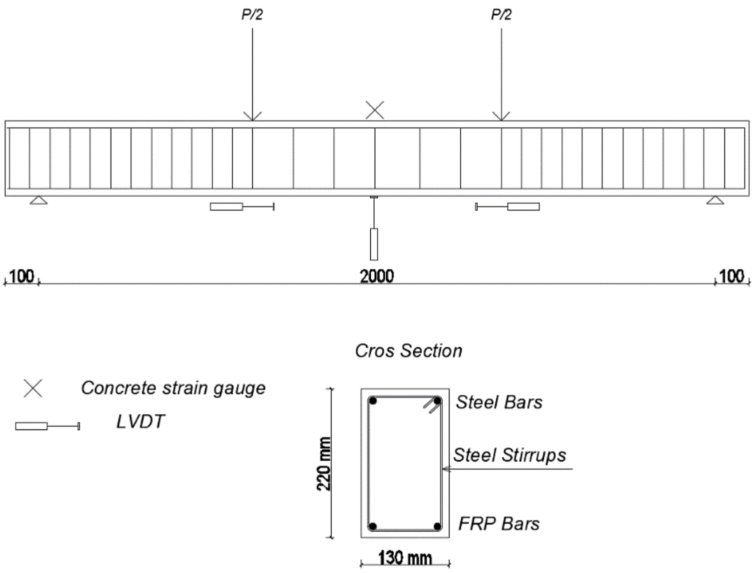

Figure 4. Beam details and instrumentation and geometrical parameters of the concrete beams

The side of each beam was marked and the corresponding loads were recorded for following the parameters. Furthermore, compression concrete zones were instrumented to measure the strain of concrete and another measuring instrument was inserted mid-span in the beam to measure the deflection. All beam specimens were tested under a four-point bending over a clean span of 200 cm (Figure 4). The load was monotonically applied using a 400 kN hydraulic actuator with a stroke-controlled rate of 300 N/s. The actuator, strain gauges, and Linear variable differential transformers were connected to a data acquisition unit to continuously record their readings during examination (Figure 5).

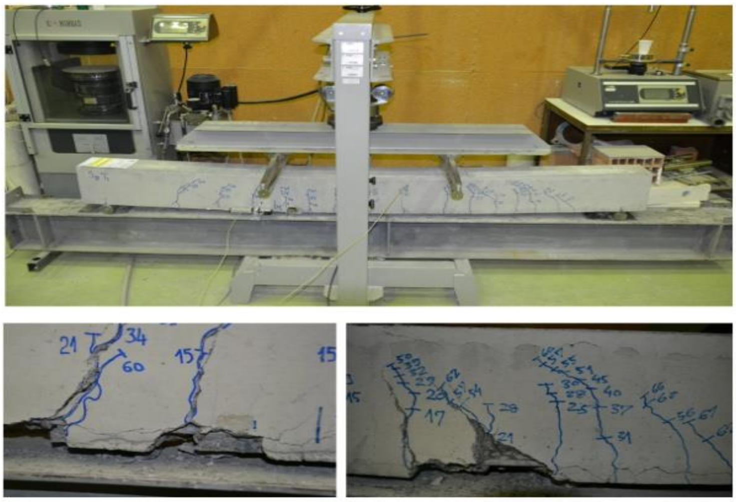

Figure 5. Instrumentation and beam examination, failure modes

During the examination, equipment software was connected to measure equipment for cracks and displacement and all necessary parameters, like displacement versus time, increments of load, the level of cracks, etc., were recorded. All the collected data were exported to an Excel spreadsheet; cracks and displacements were measured in micrometers and graphical charts were collected directly from the equipment (Figure 6).

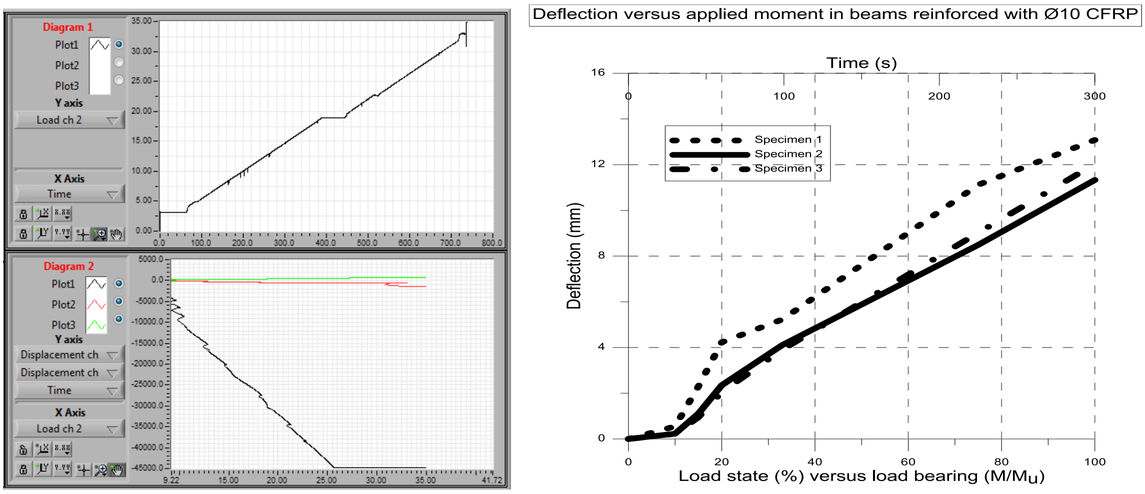

Figure 6. Displacement versus time-load chart and other parameters taken from MCC8 controls equipment

The mechanical properties of FRP bars were examined based on the American society of testing materials method. The edges of the bars were embedded inside engraved metallic cylinders to avoid constriction or shear stress of the FRP bars as shown in Figure 7. The properties of conventional steel are used from known parameters based on the previous research works for S 500. FRP bars used in this research were Glass and Carbon fiber bars which were examined based on ASTM D 7205 [19]. The mechanical properties of examined bars are presented in Table 2.

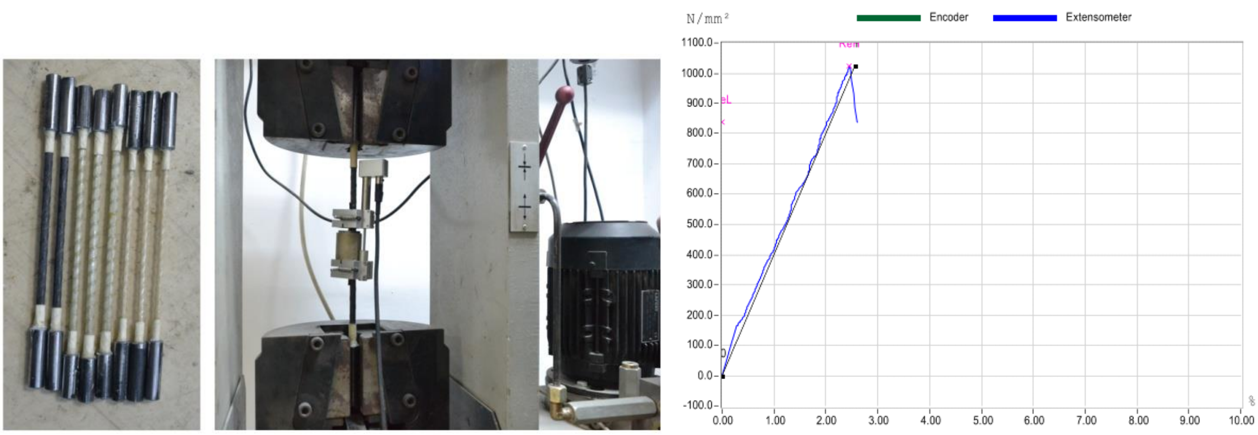

Figure 7. Specimens, testing and determination of mechanical properties of FRP bars [23]

Table 2. Mechanical properties of used FRP and conventional bars (GFRP – Glass Fiber Reinforced Polymers, CFRP – Carbon Fiber Reinforced Polymers)

An example of a column heading	GFRP Ø6	GFRP Ø8	GFRP Ø10	CFRP Ø8	CFRP Ø10
Strain ε^{*}_{frp}	0.0204	0.0234	0.0256	0.0095	0.015
Tensile strength (MPa)	1022.1	1108.02	1194.3	1265.4	2000
Elasticity modulus (GPa)	55	55	55	155	155

3. Different Approaches of Adhesion Coefficients k_b

The determination of k_b, based on the American Concrete Institute standards derived by cracks, using modifying the Gergely–Lutz Equation 1. Some typical k_b predicted values for deformed GFRP bars cited in ACI are between 0.8 and 1.80. However, the ACI Codes and Manuals suggested that designers assume a value of 1.2 for deformed GFRP bars unless more specific information was available for a particular bar. ACI Committee 440 has modified the Gergely-Lutz equation for use with concrete members incorporating the effects of different bonds and mechanical properties of FRP [20-22]. Crack width calculation according to ACI 440.1R-06 & CSA.

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

where w is the crack width.

According to Canadian standards, the value of k_b should be determined form the value of measured cracks in the bars reinforced with FRP bars at the Serviceability Limit State. Considering this recommendation, Equation 2 was used to determine the values of k_b. In this equation, the measured values of cracks are used.

$$k_b = \frac{E_f\cdot w}{2.20\cdot\beta\cdot f_f\cdot\sqrt[3]{d_c\cdot A}} \tag{2}$$

4. Test Results and Discussion

As is shown in Figure 3, except vertical cracks also appeared horizontal cracks (Figure 8), which is an indication of the failure of the bond mechanism between concrete and FRP bars.

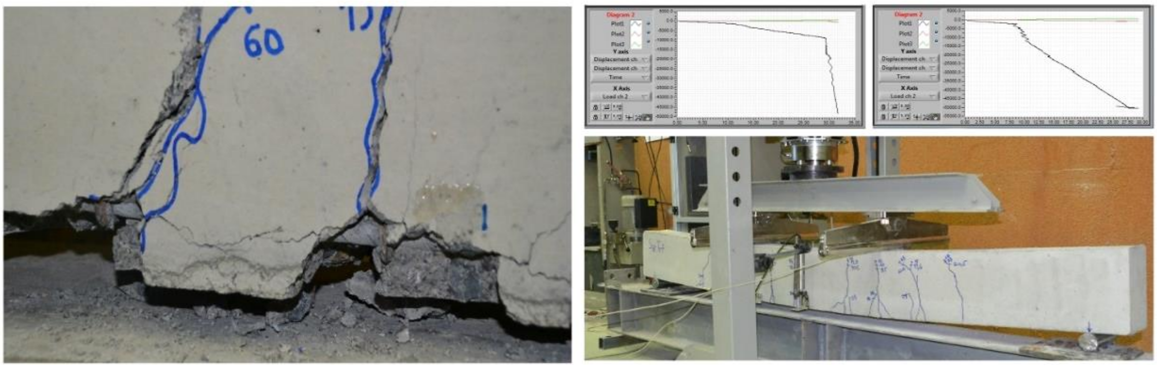

Figure 8. Testing setup and fracture mode

The bond coefficient k_b for beams reinforced with steel bars was close to 1, because the original Gergely-Lutz equation is based on steel-concrete relation. A reduction in the bond coefficient means the improvement of bond characteristics of the reinforcing bar compared to steel. Many authors agree that the percentage of Serviceability Limit Stages of elements reinforced with FRP bars is close to 30%, which is supported by this study, as shown in Table 2 in which are presented the maximum resistance and the percentage of usability of each element. During the testing of beams, following the recommendation of different standards the evaluation of k_b coefficient should be done in Serviceability Limit State, however, even in Ultimate Limit State which according to the standards is when deflections exceed the allowed value or when the cracks exceed the value of 0.7 mm, the measurement of cracks and deflections were done. This in order to see the maximum strength of these elements (Table 2). It has been observed that these elements in almost all cases are destroyed by concrete crushing. Despite the evaluating of bars even after leaving SLS, the bond coefficient evaluation was done within the SLS as recommended by several standards. The calculated and measured values for all beams for different levels of load are presented in Table 3.

Table 3. Maximum strength and percentage of SLS

An example of a column heading	Maximum strength (kN)	SLS percentage (%)
GFRP Ø6	29.24	28.0
GFRP Ø6	35.00	27.4
GFRP Ø8	37.00	25.7
GFRP Ø8	43.00	24.5
GFRP Ø10	70.00	22.0
GFRP Ø10	72.11	21.7
CFRP Ø8	59.00	40.2
CFRP Ø8	72.00	29.1
CFRP Ø8	72.90	32.0
CFRP Ø10	80.00	36.4
CFRP Ø10	85.00	32.7
CFRP Ø10	84.00	33.7

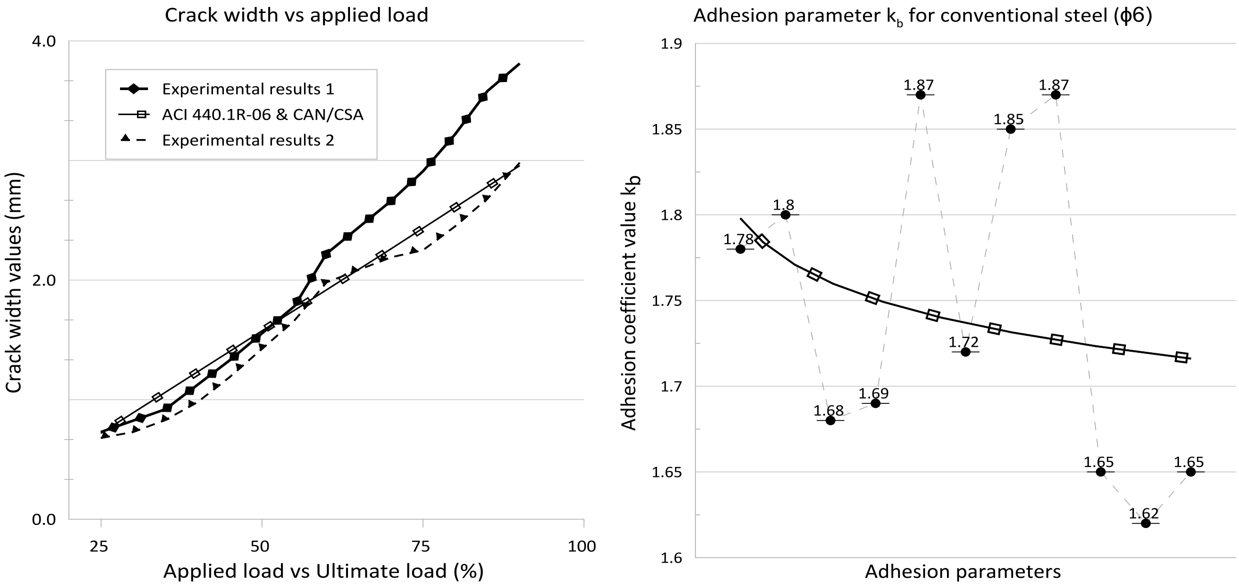

Figure 9. Crack width values in relation with applied load and adhesion parameter kb for conventional steel (Φ6)

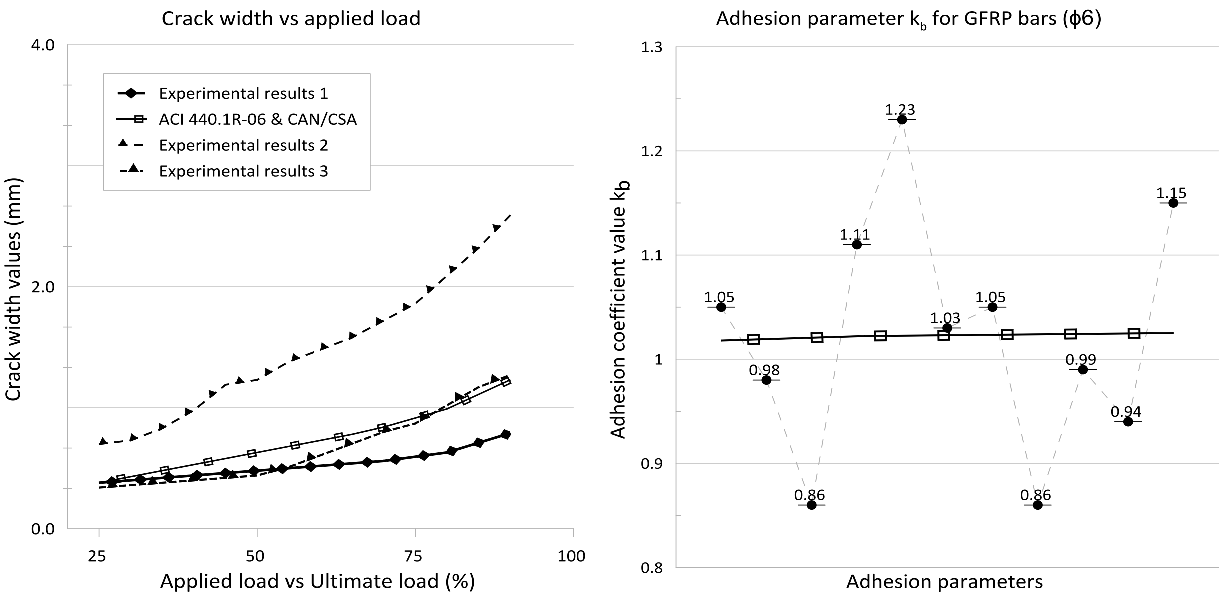

Figure 10. Crack width values for beams reinforced with CFRP bars (Φ8) and adhesion parameter kb for GFRP bars (Φ6)

The comparison of crack width values from different codes and guidelines in relation to experimental testing have showed that some codes give approximate values and other gives greater values than experimental values (Figures 9 and 10). The different technology of producing FRP bars, imposed different mechanical properties and different adhesion parameters, which complicates the arrangement for international guideline.

Table 4. Crack width values of tested beams

Beams	Code	Crack width (SLS)	Crack width (75%)	Crack width (100%)
GFRP Ø6	ACI 440.1R-06 & CAN/CSA	0.89	2.44	3.25
	EXP1	0.73	2.91	3.81
	EXP2	0.69	2.25	2.98
GFRP Ø8	ACI 440.1R-06 & CAN/CSA	0.89	2.44	3.25
	EXP1	0.71	2.91	3.81
	EXP2	0.68	2.80	3.90
GFRP Ø10	ACI 440.1R-06 & CAN/CSA	0.58	1.99	2.66
	EXP1	0.31	1.54	2.04
	EXP2	0.34	1.69	2.49
CFRP Ø8	ACI 440.1R-06 & CAN/CSA	0.38	0.92	1.23
	EXP1	0.70	1.86	2.59
	EXP2	0.38	0.60	0.79
	EXP3	0.34	0.87	1.27
CFRP Ø10	ACI 440.1R-06 & CAN/CSA	0.35	0.78	1.05
	EXP1	0.29	0.76	1.07
	EXP2	0.46	1.20	1.62
	EXP3	0.30	0.70	0.93

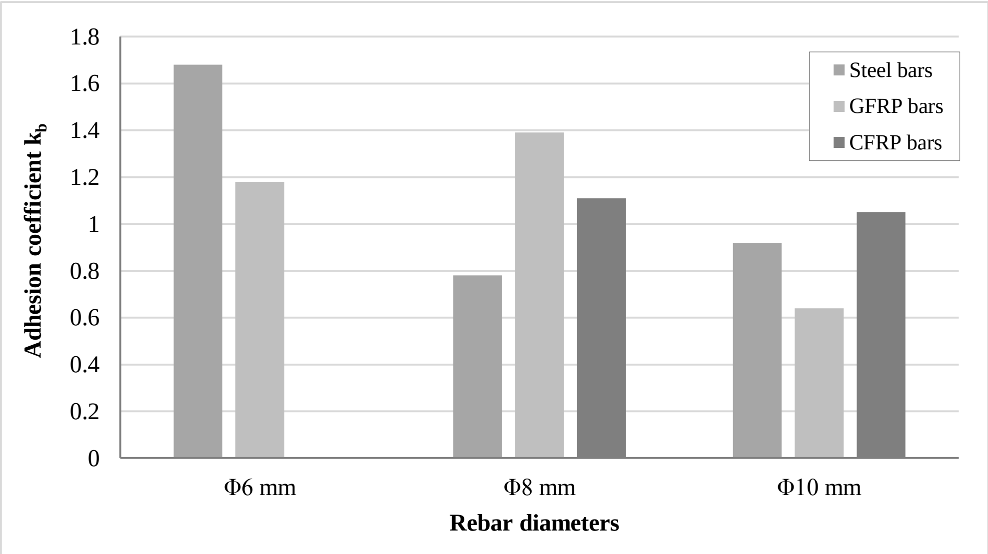

Figure 11. k_b values for different diameters

The analytical using value of k_b has a different comparison with the experimental results for different types of bars, presented in Figure 11. Because GFRP bars have a lower modulus of elasticity than CFRP bars, the failure mode of beams reinforced with GFRP occurred because of GFRP bars strain exceeding, while the failure mode of beams reinforced with CFRP bars occurred because of the sliding of CFRP rebars.

5. Conclusions

The experiment included 12 bars with 2.20 m mid-span and 130×220 mm cross-section dimensions. GFRP bars were helically grooved and CFRP bars were sand-coated surface. Based on the experimental results, we provide the following conclusions:

- The recommended value for k_b according to standards-based solely on surface configuration was not supported from this investigation because not just surface configuration but also the diameter of bars and fiber type influenced in bond coefficient value k_b;
- The influence of bar diameter in the determination of k_b is not linear, which means that increasing the bar diameter does not mean increasing the quality of the bond mechanism. CFRP bars have shown more constant values of (k_b) depending on different bar diameter while GFRP bars have shown variable values for different bar diameter;
- Based on the results obtained from this research regarding the values of cracks and deflections, it has been noticed that these values are closer to the Canadian standards (CSA) than the other standards;
- The authors conducted this investigation to determine the measured values of k_b and this experiment showed that there is a significant difference between the values determined according to different standards and the measured real values therefore we suggest that the design should be made based on the measured values, more than theoretical ones. Otherwise, to accurately determine the behavior of the bars in terms of bond coefficient, more research should be conducted in the future with a large number of measured values.

6. Declarations

6.1. Author Contributions

Conceptualization, N.K., A.K., E.K. and B.A.; writing—original draft preparation, N.K., A.K., E.K. and B.A.; writing—review and editing, N.K., A.K., E.K. and B.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

This work was supported by the laboratory of the University of Prishtina “Hasan Prishtina” in Prishtina, Kosova.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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