Newly Proposed Strain Limit for Designing Concrete Slab-on-Ground Reinforced with GFRP Rebars

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Abstract

Glass Fiber Reinforced Polymer (GFRP) rebar has been used as an alternative reinforcement in concrete slab-on-ground for years. It has many attractive engineering properties such as high tensile strength, light weight, and rust proof. To design GFRP reinforced slab-on-ground, ACI440.1R-15 suggested that the amount of GFRP rebars should be controlled by a strain limit rather than allowable stress because GFRP rebar has low modulus of elasticity. Currently, the recommended strain limit is based on strain of ordinary steel reinforcement at the steel’s allowable stress. This limit yields a very low allowable stress resulting in uneconomical and uncompetitive design compared to conventional steel rebar. Therefore, a new method to evaluate strain limit is suggested in this study. The newly proposed equation for strain limit is derived based on an acceptable crack width according to ACI440.11-22. By this method, the strain limit can be increased about thirty to sixty-five percent depending on spacing and clear covering of GFRP rebars. With the increased strain limit, the amount of required GFRP rebar can be reduced, which helps lowering the construction cost and makes GFRP rebars to be more competitive.

Keywords**:** GFRP rebar, slab-on-ground, allowable strain limit

1. Introduction

Glass Fiber Reinforced Polymer (GFRP) is a composite material having two main constituents which are polymeric matrix and glass fiber. The matrix acts as a binder holding fibers together while the fibers provide tensile strength to the material. It can be formed in various shapes and adopted in many engineering applications such as automotive, aerospace, marine, and construction. For construction applications, GFRP is used mostly in forms of sheets and rebars. The GFRP sheet is normally applied to concrete structures for a strengthening purpose. For example, it is attached to the tension side of an existing reinforced concrete beam to increase a flexural moment capacity, or it can be wrapped around a concrete column for seismic strengthening and retrofitting. Whereas the GFRP rebar is used as an alternative reinforcement in reinforced concrete instead of using conventional steel rebar. It can be formed in various diameters and lengths as shown in Fig. 1.

Fig. 1 Examples of GFRP rebars.

GFRP rebar is well-known for it’s high tensile strength. Typical GFRP rebars have tensile strength around two to three times that of steel rebars. In addition, it is light weight. Density of GFRP rebars are about one-sixth to one-fourth of density of steel rebars [1]. This makes shipping and handling much easier for GFRP rebars. One more important property of GFRP rebars is that they do not rust. The rust proof property makes GFRP rebars are very attractive to marine and offshore constructions. However, they have a few drawbacks. First, most of FRPs including GFRP are brittle material which might cause a sudden failure to a structure. Another disadvantage of GFRPs is their low modulus of elasticity. The modulus of elasticity of GFRP rebars is in the range of 30000 to 55000 MPa. The low modulus of elasticity raises concern about deflection and crack control of reinforced concrete. However, several design guides and codes [2-4] have requirements such as minimum reinforcement ratio and maximum rebar spacing to avoid sudden failure and excessive crack width.

GFRP rebars have been used to reinforce both structural and non-structural concrete members such as bridge decks, beams, columns, and barriers. One of the structures that is often constructed associated with GFRP rebars is a slab-on-ground which can be found as road pavement, garage floor, and slab for factory and warehouse. Typically, slab-on-ground is reinforced by steel rebars. The provided rebars are neither for flexural nor shear capacities because the applied forces are transferred through the slab to the ground. The objective of providing reinforcements in slab-on-ground is mainly for crack control. For the steel reinforced slab-on-ground, it is designed by assuming that when temperature rises or falls the slab expands or contracts creating movements. These movements generate friction between the slab and the subgrade. To statically balance the friction force, internal tensile force occurs inside the concrete slab and the maximum tensile force is assumed to initiate in the middle of the slab as shown in Fig. 2.

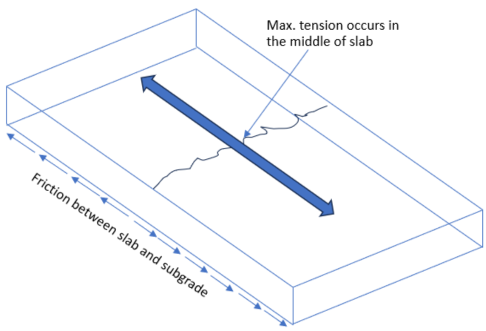

Fig. 2 Behavior of slab-on-ground.

The required steel reinforcements to resist the maximum tensile force can be quantified by considering a free body diagram of a one-meter strip of a slab-on-ground as shown in Fig. 3.

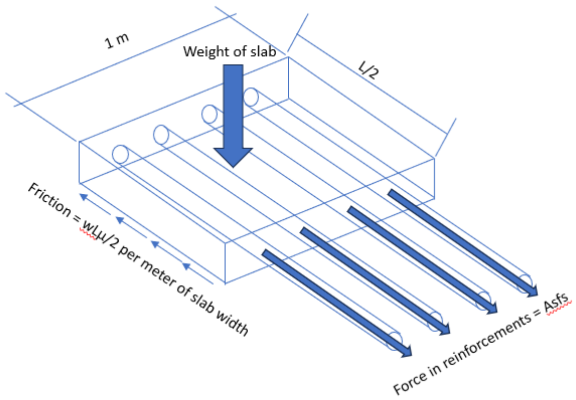

Fig. 3 Free body diagram of slab-on-ground.

Equating force in reinforcements to friction and substituting the allowable stress (f_{allow}) for the reinforcement stress (f_s) obtains the required amount of reinforcement (A_s) as shown in Eq. (1).

$$A_s = \frac{\mu L w}{2 f_{allow}} \tag{1}$$

Where, A_s is area of the required reinforcement per linear meter, L is the length of the slab (joint to joint), μ is the friction coefficient for subgrade. The Portland Cement Association [5] recommends μ = 1.5 for slab-on-ground, f_{allow} is the allowable stress, and w is the weight of slab per square meter.

Eq. (1) is valid for all slab-on-grounds regardless of reinforcement material. However, because GFRP rebars have low modulus of elasticity, ACI 440.1R-15 requires that strain limit shall be used to design slab-on-ground reinforced by GFRP rebars instead of using allowable stress. Thus Eq. (1) becomes.

$$A_f = \frac{\mu L w}{2(0.0012 E_f)} \tag{2}$$

Where, A_f is the area of required GFRP rebars per linear meter, E_f is the modulus of GFRP rebars, and 0.0012 is the recommended strain limit, which is approximately the same as a strain of steel rebars at allowable stress.

In the market, the maximum modulus of GFRP rebars is around 55000 MPa. By using modulus equal to 55000 MPa in Eq. (2), GFRP rebars will have an allowable stress of 66 MPa for slab-on-ground design, which is significantly lower than the 240 MPa for steel rebars with a modulus of 200000 MPa. Consequently, the required area of GFRP rebars is about 3.6 times greater than that of steel rebars even though the strength of GFRP rebars is two to three times higher than that of steel rebars. This yields uneconomical and uncompetitive design compared to ordinary steel rebars.

Furthermore, there are couple reasons to believe that using strain limit of 0.0012 for GFRP rebars is inappropriate. First, there are some properties affecting cracks in concrete slab such as rebar spacing and clear cover of the rebar but using 0.0012 as a strain limit does not account on effects of those properties. Second, the strain limit for GFRP rebar should not be identical to that of steel rebar. The purpose of strain limit is to control crack width preventing steel rebar from corrosion which is one of the common causes of damage in reinforced concrete structure. However, GFRP rebars are not vulnerable to corrosion. In addition, ACI440.1R-06 also recommended that the maximum crack width limit for concrete reinforced by FRP rebar can be relaxed because FRP rebars are corrosion resistant. Therefore, the strain limit for GFRP rebar could be higher than the limit for steel rebar. Thus, a new equation for computing strain limit of GFRP rebar, which will be used instead of 0.0012 in Eq. (2), is proposed in this study. The equation is based on an equation for crack control by distributing GFRP rebar given in ACI440.11-22. The proposed equation includes effects of rebar spacing and concrete cover. In addition, the proposed equation is derived using “acceptable” crack width indicated in ACI CODE-440.11-22. In other words, the strain limit calculated from the proposed equation will yield an acceptable crack width.

2. Crack control by limit rebar spacing

In 2006, ACI440.1R-06 provided an equation to evaluate crack width, which is based on a study by [6]. According to ACI440.1R-06, crack width may be computed by Eq. (3).

$$w_c = 2\frac{f_f}{E_f}\beta k_b\sqrt{d_c^2 + \left(\frac{s}{2}\right)^2} \tag{3}$$

Where, w_c is the maximum crack width, f_f is the maximum tensile stress in rebars, β is the ratio of distance between neutral axis to extreme tension fiber to distance between neutral axis and centroid of reinforcement, d_c is the thickness of covering measured from tension face to center of the closest rebar, s is the rebar spacing, and k_b is the coefficient accounting for bond between GFRP rebar and concrete which can be in the range from 0.60 to 1.72. The code also suggested that k_b of 1.4 is conservative enough for GFRP rebar without test data. Therefore, k_b of 1.4 is used throughout this study. By using Eq. (3), the maximum crack width can be quantified and compared to the crack width limits. ACI440.1R-06 suggested the crack limits of 0.5 mm and 0.7 mm for exterior and interior structures, respectively.

To avoid the impracticality of directly measuring crack width, an indirect approach is adopted, wherein crack width is not explicitly calculated and compared to allowable limits. In 2007, Ospina and Bakis [7] proposed an indirect flexural crack control equation which limits a maximum FRP bar spacing associated with desired crack width limit. Then, the equation is adopted by ACI440.1R-15 and shown in Eq. (4).

$$s_{max} = 1.15\frac{E_f w}{f_{fs} k_b} - 2.5c_c \tag{4}$$

Where, s_{max} is the maximum FRP bar spacing, c_c is the clear cover, f_{fs} is the stress induced in FRP bar at service loads, and w is the maximum allowable crack width. In 2022, ACI CODE-440.11-22 suggested using an acceptable crack width of 0.7 mm throughout the code and Eq. (4) becomes.

$$s_{max} = 0.81\frac{E_f}{f_{fs} k_b} - 2.5c_c \tag{5}$$

3. The proposed equation for computing strain limit and required reinforcement

The proposed equation is not a newly derived equation, but it is a re-arrange version of Eq. (5). Notably, the term E_f/f_{fs} is an invert of strain. By re-arranging Eq. (5) obtains.

$$\varepsilon_{lim} = \frac{f_{fs}}{E_f} = \frac{0.81}{k_b(s+2.5c_c)} \tag{6}$$

The strain limit obtained from the proposed equation is a function of both rebar spacing (s) and clear cover (c_c). Moreover, the acceptable crack width is embedded in “0.81”. By substitute strain limit obtained from Eq. (6) into Eq. (2) (instead of using strain equal to 0.0012) and use k_b of 1.4, the required GFRP rebar area becomes.

$$A_f = \frac{0.864\mu L w(s+2.5c_c)}{E_f} \tag{7}$$

With embedded acceptable crack width, it implies that if the provided reinforcement is not less than A_f obtained from Eq. (7), the crack occurring in the slab will not be wider than an acceptable crack width of 0.7 mm.

4. The maximum strain limit and bar spacing limitation

ACI CODE-440.11-22 not only requires the bar spacing to be not greater than the spacing obtained from Eq. (5) but also provides the upper bound limit for bar spacing as shown in Eq. (8).

$$s = \frac{0.66E_f}{f_{fs}k_b} \tag{8}$$

Re-arranging Eq. (8) obtains the maximum strain limit as shown in Eq. (9), which can be used as an upper bound of the strain limit given in Eq. (6).

$$\varepsilon_{max} = \frac{0.66}{sk_b} \tag{9}$$

In addition, designers should keep in mind that the proposed equation is valid for the bar spacing not greater than the bar spacing required by Eq. (8). This limitation ensures that the strain limit obtained by Eq. (6) is also valid according to the code.

5. Comparison of required GFRP rebars

The main purpose of this study is suggesting a new equation to make GFRP rebars become more competitive for slab-on-ground design. Therefore, in this section, the required GFRP rebars obtained by using Eq. (2) are compared to those acquired from using Eq. (7). For a fair comparison, modulus of 55000 MPa is used in both equations. Furthermore, most of slab-on-grounds are reinforced by only one layer of reinforcements in the middle of their thickness. Thus, clear covering of the rebars is a function of the slab's thickness (T_t), which can be computed as the thickness minus rebar's diameter (d_b) and divided by two as shown in Eq. (10). Therefore, four typical thicknesses of slab-on-ground are selected.

$$c_c = \frac{T_t - d_b}{2} \tag{10}$$

In addition, rebar spacing is also an important factor controlling the required amounts of GFRP rebars. From Eq. (7), the required GFRP rebars vary linearly to the spacing. Thereby, two rebar spacings are used for each slab thickness. Finally, the amounts of required GFRP rebars calculated using Eq. (2) and Eq. (7) are presented in table 1.

Table 1. Amounts of required GFRP rebar (mm^2/m).

Slab THK. (mm)	Req. A_f (Eq. 2)	Req. A_f (Eq. 7)	
		150 mm spacing	200 mm spacing
150	210	125	140
200	280	195	220
250	350	280	310
300	420	385	420

Results in table 1 indicate that the required GFRP can be reduced up to forty percents by using the proposed equation. Moreover, the comparison shows that a thicker slab requires a greater amount of GFRP rebars. This is true for required GFRP computed by both equations. However, the thickness affects the amount of required GFRP in different rates for each equation as shown in Fig. 4.

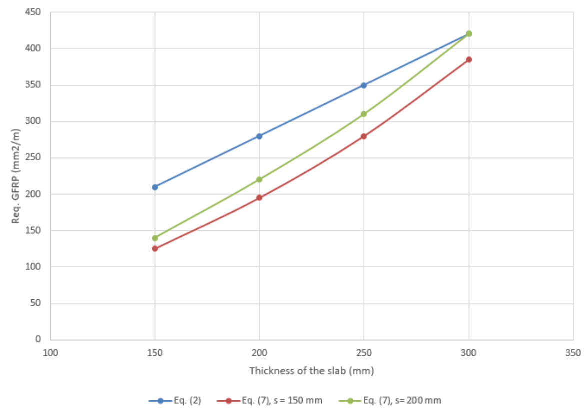

Fig. 4 Relationship between slab thickness and required GFRP rebars.

The thicker the slab, the heavier, which causes a greater friction underneath the slab. So, the required GFRP amounts are increased. Mathematically, Fig. 4 shows that the required GFRP from Eq. (2) varies linearly to the slab thickness. On the other hand, the required GFRP from Eq. (7) exhibits second-order polynomial relationship with the thickness. This is because the thickness affects both weight and clear covering. Eq. (2) contains only weight of the slab. Thus, the required GFRP is a linear function of the thickness, while the required GFRP from Eq. (7) is a function of weight multiplied by clear covering. As a result, the required GFRP varies parabolically with the thickness. Even though, the required GFRP from Eq. (7) increasing faster than that from Eq. (2), the required amounts can be less when select "suitable" rebar spacing. For example, with the slab 300 mm thick, the required amount of GFRP can be reduced from 420 mm^2/m to 385 mm^2/m by changing rebar spacing from 200 mm to 150 mm. Fig. 5 illustrates that, with the same slab thickness, the required GFRP can be reduced by decreasing rebar spacing.

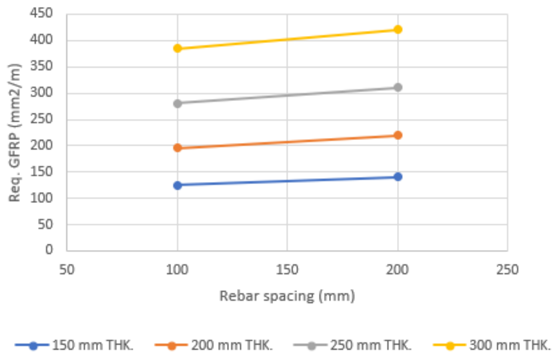

Fig. 5 Relationship between rebar spacing and required GFRP rebars.

This also implies that, with the same amount of GFRP rebar, the closer spacing yields a smaller strain and crack width. For designer point of view, it is better to use smaller rebar diameter with closer spacing than use a bigger bar with wider spacing.

6. Conclusions

This study presents a revised approach to designing GFRP-reinforced slab-on-ground structures by proposing a more rational strain limit equation that considers rebar spacing and concrete cover. While current design practice adopts a constant strain limit of 0.0012 (originally derived for steel reinforcement). This research demonstrates that such an approach does not fully leverage the unique properties of GFRP, particularly its corrosion resistance. The proposed equation, based on crack control principles and code-accepted limits, results in more economical designs.

Through comparative analysis, it was shown that the proposed method can significantly reduce the required amount of GFRP reinforcement under specific configurations, making GFRP a more competitive alternative to steel in slab-on-ground applications. The findings emphasize that slab thickness, rebar spacing, and concrete cover all play crucial roles in optimizing GFRP use. Ultimately, the study advocates for the adaptation of design codes to reflect the material behavior of GFRP more accurately, thus unlocking its full potential in structural engineering.

7. Future work

The proposed method is currently on a numerical study process. Experimental study to verify the equation should be performed.

References

[1] Nanni, A., DeLuca, A. and Jawaheri Zadeh, H. (2014). *Reinforced Concrete with FRP Bars-Mechanics and Design*. The CRC Press Taylor & Francis Group.

[2] ACI 440.1R-06-Guide for Design and Construction of Structural Concrete Reinforced with FRP Bars.

[3] ACI 440.1R-15-Guide for Design and Construction of Structural Concrete Reinforced with FRP Bars.

[4] ACI 440.11-22-Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars-Code and Commentary.

[5] Portland Cement Association. (1990). *Concrete Floor on Ground*.

[6] Frosch, R. J. (1999). Another Look at Cracking and Crack Control in Reinforced Concrete. *ACI Structure*, 96, pp. 437-442.

[7] Ospina, C. E. and Bakis, C. E. (2007). Indirect Flexural Crack Control of Concrete Beams and One-Way Slabs Reinforced with FRP Bars. *The 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures (FRPCS-8)*, Patras, Greece, 16-18 July 2007.