Design Program of Reinforced Concrete Section with GFRP Rebar

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Abstract

According to modern technology, structures have several types of material to use in design. One of the most widely used is Glass Fiber Reinforced Polymer. It is used in bridges, rail plinths, precast applications, marine structures and tunnel constructions. Prominent features of GFRP are long service life, impervious to chloride ion and chemical attack, thermally and electrically nonconductive, and high fatigue endurance. This paper presents design program of reinforced concrete section with Glass Fiber Reinforced Polymer rebar. This design program provides design of beam and slab. The program written by Python can increase accuracy of calculations and decrease time to design. The design criteria used in this paper was ACI440.1R-15 and ACI318-08.

Keywords: GFRP; Design program; Design section; Slab; Beam

1. Introduction

Since the structures were formed, they have been plagued by deterioration and destruction. Human started to create some materials which have more durability and low maintenance costs. GFRP rebars are used in bridges, rail plinths, precast, marine structures and tunnel construction. GFRP rebars become more widely use because of their advantages (e.g., impervious to chloride ion and chemical attack, service life much greater than steel in corrosive environment, etc.). Fiber-reinforced polymer reinforcement has a high tensile strength, lower creep-rupture threshold and exhibits linear stress-strain behavior to failure[1]. All of advantages lead GFRP reinforced to be an option of reinforced materials that used in general constructions.

1.1 Motivation and significance

Several years ago, hand calculation is used for design members, but these days, modern technology made a new alternative for design member such as program. Furthermore, hand calculation is not widely used because of their limitations. For instance, hand calculation does not have enough accuracy. It increases operation costs, material costs and maintenance costs. In addition, it takes time to design with hand calculation because it is calculated from human. Therefore, design program helps decrease limitations of hand calculation and design member more efficient. In addition, they also have an alternative material. GFRP have become more used for recent years because of their beneficial properties. Therefore, all of these interesting alternatives inspire us to create design program of reinforced concrete section with GFRP rebar.

1.2 Project objective

The objectives of this project are to (1) help design cross-sectional of slab and beam with GFRP rebars, (2) be an alternative program for using GFRP rebars, and (3) decrease mistakes and increase accuracy from calculations.

1.3 Scope of Work

This program designs cross-sectional of beam and slab with proper GFRP rebars. It can design with two alternatives of moment; (1) maximum moment when a user inputs loads in design program, and (2) factored moment at any point when a user inputs moment in design program. It can also design shear force at any section. There is some information that a user has to input such as a span length, specified compressive strength of concrete, or exposure conditions etc. The data in program can design only in GFRP design, except for user change the data into other types of FRP rebars. Furthermore, there is some information that a user can change from its default such as beam width, ultimate strain in concrete, covering, or size of GFRP rebars etc. This program can show full and short calculations of designed member with a sketch of the design.

2. Material Characteristics

Fiber-reinforced polymer can be manufactured using a variety of techniques. Therefore, the material characteristics may not use in all products because it is considered with specific data.

Table 1 Typical tensile properties of reinforcing bars* [1]

	Steel	GFRP	CFRP	AFRP
Normal yield stress, MPa	276 to 517	NA	NA	NA
Tensile strength, MPa	483 to 1600	483 to 690	600 to 3690	1720 to 2540
Elastic modulus, GPa	200	35 to 51	120 to 580	41 to 125
Yield strain, percent	0.14 to 0.25	NA	NA	NA
Rupture strain, percent	6.0 to 1.2	1.2 to 3.1	0.5 to 1.7	1.9 to 4.4

2.1 Mechanical properties and behavior

2.1.1 Tensile behavior

When loaded in tension, FRP bars exhibit no plastic behavior before rupture. The tensile properties of some commonly used FRP bars are summarized in Table 1.

2.1.2 Compressive behavior

While design of FRP bars to resist compressive stresses is not recommended, the following section is presented to fully describe the behavior of FRP bars. Standard test methods are not yet established to characterize the compressive behavior of FRP bars.

3. Design Philosophy

The recommendations of FRP bars are based on principles of equilibrium and compatibility, and the constitutive laws of the material. The failure behavior of both FRP reinforcement and concrete allows for consideration to be given to either compression-controlled or tension-controlled modes of flexural failure. All load factored that used in design of member are based on ACI318-08[2]. The design method follows from ACI 440.1R-15[1].

Table 2 Environmental reduction factor[1]

Exposure condition	Fiber type	Environmental reduction factor C_E
Concrete not exposed to earth and weather	Carbon	1.0
	Glass	0.8
	Aramid	0.9
Concrete exposed to earth and weather	Carbon	0.9
	Glass	0.7
	Aramid	0.8

3.1 Design material properties

There is specific data that taken from manufacturer such as the guaranteed tensile strength. The design tensile strength, f_{fu} should be determined by Eq. (3.1). The design rupture strain, ε_{fu} should be determined by Eq. (3.2).

$$f_{fu}=C_E f_{fu}^{*} \tag{3.1}$$

$$\varepsilon_{fu}=C_E \varepsilon_{fu}^{*} \tag{3.2}$$

The environmental reduction factors, C_E given in Table 2 are conservative estimates. Minimum clear cover of FRP reinforced concrete member shall be $2d_b$ or 30 mm, whichever is greater[3].

3.2 Flexure

3.2.1 General conditions

The design of GFRP reinforcement is similar to the design of steel-reinforced concrete.

a) Flexural design philosophy

The design of GFRP reinforcement is similar to the design of steel-reinforced concrete. Both compression- and tension-controlled sections are acceptable in the design of flexural members reinforced with FRP bars.

b) Assumptions

There are assumptions used in this chapter; (1) strain in concrete and the FRP reinforcement is proportional to the distance from the neutral axis; (2) the maximum usable compressive strain in the concrete is assumed to be 0.003; (3) the tensile strength of concrete is ignored; (4) the tensile behavior of the FRP reinforcement is linearly elastic until failure; (5) a perfect bond exists between concrete and the FRP reinforcement.

3.2.2 Flexural strength

The strength design philosophy states that the design flexural strength, ϕM_n at a section of a member should exceed the factored moment (Eq. (3.3)). The factored moment, M_u refers to the moments calculated by the use of factored loads as prescribed in ACI 318-08[2].

$$\phi M_n \geq M_u \tag{3.3}$$

a) Strength limit state

The controlling limit state can be determined by comparing the FRP reinforcement ratio to be the balanced reinforcement ratio, which is a ratio where concrete crushing and FRP rupture occur simultaneously. The FRP reinforcement ratio, ρ_f can be computed from Eq. (3.4). The balanced FRP reinforcement ratio, ρ_{fb} can be computed from Eq. (3.5).

$$\rho_f = \frac{A_f}{bd} \tag{3.4}$$

$$\rho_{fb} = 0.85\beta_1 \frac{f_c'}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}} \tag{3.5}$$

If the reinforcement ratio is less than the balance ratio ($\rho_f < \rho_{fb}$), the FRP rupture limit state control. Otherwise, ($\rho_f > \rho_{fb}$) the concrete crushing limit controls.

b) Nominal flexural strength

When $\rho_f > \rho_{fb}$, the controlling limit state is crushing of the concrete. Based on the equilibrium of force and strain compatibility, the following can be derived

$$M_n = \rho_f f_f \left(1 - 0.59 \frac{\rho_f f_f}{f_c'}\right) bd^2 \tag{3.6}$$

When $\rho_f < \rho_{fb}$, the controlling limit state is rupture of the FRP reinforcement, and the nominal flexural strength at a section can be as

$$M_n = A_f f_{fu} \left(d - \frac{\beta_1 c}{2}\right) \tag{3.7}$$

c) Strength reduction factor for flexure

Because FRP members do not exhibit ductile behavior, a conservative strength reduction factor should be adopted to provide a higher reserve of factor strength in a member. The strength reduction factor, ϕ for flexure can be computed by Eq. (3.8).

$$\phi = \begin{cases} 0.55 \text{ for } \rho_f \leq \rho_{fb} \\ 0.3 + 0.25 \dfrac{\rho_f}{\rho_{fb}} \text{ for } \rho_{fb} < \rho_f < 1.4\rho_{fb} \\ 0.65 \text{ for } \rho_f \geq 1.4\rho_{fb} \end{cases} \tag{3.8}$$

d) Minimum FRP reinforcement

If a section is tension controlled ($\rho_f \leq \rho_{fb}$), a minimum amount of reinforcement should be provided to prevent failure upon concrete cracking, $\phi M_n \geq M_{cr}$ where M_{cr} is the cracking moment. If the section is not tension controlled, the minimum amount of reinforcement to prevent failure upon cracking is automatically achieved.

$$\varnothing M_n \geq M_{cr} \tag{3.9}$$

$$A_{f,min} = \frac{0.41\sqrt{f_c'}}{f_{fu}} b_w d \geq \frac{2.3}{f_{fu}} b_w d \tag{3.10}$$

3.2.3 Serviceability

a) cracking

To be consistent with ACI 318-08[2], flexural crack control in FRP-reinforced concrete beams and one-way slabs can be accomplished by specifying a maximum FRP bar spacing, s_{max} equal to

$$s_{max} = 1.15 \frac{E_f w}{f_{fs} k_b} - 2.5 c_c \leq 0.92 \frac{E_f w}{f_{fs} k_b} \tag{3.11}$$

$$\mathrm{w} = 2 \frac{f_f}{E_f} \beta k_b \sqrt{d_c^2 + \left(\frac{s}{2}\right)^2} \tag{3.12}$$

In situations where crack widths, *w* are limited by aesthetic reasons, limiting crack widths in range of 0.4 to 0.7 mm are generally acceptable. The consensus of the committee 440, for the case where k_b is not known from experimental data, is that a conservative value of 1.4 should be assumed.

b) Deflections

In general, ACI 318-08, Table 9.5(a)[2] ,for deflections control are concerned with deflections that occur at service levels under immediate and sustained static loads.

i. Effective moment of inertia

In general, ACI 318-08, Table 9.5(a)[2] ,for deflections control are concerned with deflections that occur at service levels under immediate and sustained static loads. *Effective moment of inertia.* Gao et al., concluded that to account for reduced tension stiffening in FRP-reinforced members, a modified expression for the effective moment of inertia, I_e is required. [10] This expression is recommended and is given by Eq. (3.13). The factor β_d is a reduction coefficient related to reduced tension stiffening exhibited by FRP-reinforced members, the committee recommends the following from Eq. (3.14).

$$I_e=\left(\frac{M_{cr}}{M_a}\right)^3\beta_d I_g+\left[1-\left(\frac{M_{cr}}{M_a}\right)^3\right]I_{cr}\leq I_g \text{ where } M_a\geq M_{cr} \qquad (3.13)$$

$$\beta_d=\frac{1}{5}\left(\frac{\rho_f}{\rho_{fb}}\right)\leq 1.0 \qquad (3.14)$$

ii. Calculation of deflection (direct method)

According to ACI 318-08[2], the long-term deflection due to creep and shrinkage $\Delta_{(cp+sh)}$ can be computed according to

$$\Delta_{(cp+sh)}=\lambda_\Delta(\Delta_i)_{sus} \qquad (3.15)$$

$$\lambda_\Delta=\frac{\xi}{1+50\rho'_f} \qquad (3.16)$$

The parameter in λ_Δ in Eq. (3.16) reduces to ξ because compression reinforcement is not considered for FRP-reinforced members ($\rho_f{}'$=0). Value of ξ equal to 2 (recommended by ACI 318-08[3] for a duration more than five years).

3.2.4 Creep rupture and fatigue

a) Creep rupture stress limits

To avoid failure of an FRP-reinforced member due to creep rupture of the FRP, stress limits should be imposed on the FRP reinforcement. The stress level in the FRP reinforcement, f_{fs} can be computed using Eq. (3.17), with $M_{s,sus}$ equal to the unfactored moment due to all sustained loads.

$$f_{f,suss}=M_{s,sus}\frac{n_f d(1-k)}{I_{cr}} \qquad (3.17)$$

b) Fatigue stress limits

The structure is subjected to the fatigue regimes, the FRP stress should be limited to the values. The FRP stress can be calculated by replacing $M_{s.sus}$ with the moment due to all sustained loads plus maximum moment induced in a fatigue loading cycle.

3.3 Shear

3.3.1 General conditions

Several issues should be considered for the shear design of FRP-reinforced members. Fiber-reinforced has: (1) a relatively low modulus of elasticity; (2) a low transverse shear resistance; (3) a high tensile strength and no yield point.

a) Shear design philosophy

The design of FRP shear reinforcement is based on the strength design method. The strength reduction factor of 0.75 given by ACI 318-08[2].

3.3.2 Shear strength of FRP-reinforced members

The concrete shear capacity V_c of using FRP can be evaluated according to

$$V_c=\frac{2}{5}\sqrt{f'_c}\,b_w(kd) \qquad (3.18)$$

The stress level in the FRP shear reinforcement should be limited to control shear crack widths and maintain shear integrity of the concrete and to avoid failure at the bent portion of the FRP stirrup, f_{fb} (Eq. (3.20)). Equation (3.19) gives the stress level in the FRP shear reinforcement at ultimate for use in design, f_{fv}

$$f_{fv}=0.004E_f\leq f_{fb} \qquad (3.19)$$

$$f_{fb}=\left(0.05\frac{r_b}{d_b}+0.3\right)f_{fu}\leq f_{fu} \qquad (3.20)$$

a) Limits on tensile strain of shear reinforcement

The design assumption that concrete and reinforcement capacities are added is accurate when shear cracks are adequately controlled. CAN-S6S1-10 adopted the 0.004 limit in the shear design of concrete members reinforced with FRP stirrups.[4]

b) Minimum amount of shear reinforcement

ACI 318 requires a minimum amount of shear reinforcement, $A_{f.min}$ when V_u exceeds $\phi V_c/2$. The requirement is to prevent or restrain shear failure in members where the sudden formation of cracks can lead to excessive distress[14].

3.3.3 Detailing of shear stirrups

The maximum spacing of vertical steel stirrups given in ACI 318-08[2] as the smaller of d/2 or 600 mm. is used for vertical FRP shear reinforcement. In addition, FRP stirrups should be closed with 90-degree hooks.

3.4 Shrinkage and temperature reinforcement

3.4.1 minimum FRP reinforcement ratio

Stated in ACI 318-08[2], the ratio of reinforcement to gross area of concrete should be at least $0.0018\text{x}414/f_y$, where f_y is MPa, but not less than 0.0014. Therefore, when deformed FRP shrinkage and temperature reinforcement is used, the amount of reinforcement should be determined by using Eq. (3.21). The upper limit for the ratio of temperature and shrinkage reinforcement, $\rho_{f,ts}$ equal to 0.0036.

$$\rho_{f,ts} = 0.0018 \times \frac{414}{f_{fu}} \frac{E_s}{E_f} \qquad (3.21)$$

3.5 Development of reinforcement

3.5.1 Bar location modification factor

The default bar location modification factor is 1.0. For bars with more than 300 mm of concrete cast below, α in Eq. (3.22) should be taken as 1.5.

3.5.2 Development of positive moment reinforcement

The development length, l_d for straight bars is defined as the bond length required to develop f_{fr} and is given by

$$l_d = \frac{\alpha \dfrac{f_{fr}}{0.0083\sqrt{f_c'}} - 340}{13.6 + \dfrac{C}{d_b}} d_b \qquad (3.22)$$

4. Outputs

4.1 Software information

In this designing program, there are beam section design and slab section design. For beam design, there are two options which are: 1) Design sectional of maximum moment of beam; 2) Design sectional at any section

From the information above, in particular 3. Design-Philosophy that shows the equations and data are used for creating software working process.

4.2 Software limitation

In this software, limitations have (a) only for single reinforcement; (b) design criteria used in this program are ACI440.1R-15 and ACI318-08; (c) GFRP size from CSA S807-10; (d) only for simply supported.

4.3 Input and Output

4.3.1 Beam Design (Design sectional at max. moment)

Input : L, f_c', w_{LL}, w_{SDL} (*not include self-weight), and Exposure Condition.

Output : Section of beam that calculated from input and its drawing.

4.3.2 Beam Section Design (Design at any sectional)

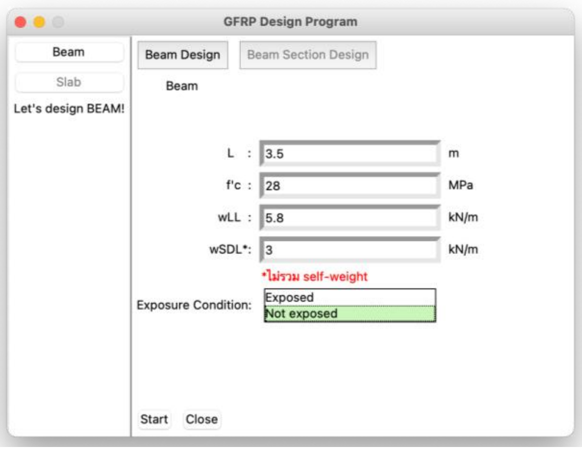
Input : L, f_c', M_{LL}, M_{SDL} (*not include self-weight), V, and Exposure Condition.

Output : Section of beam that calculated from input and its drawing.

4.3.3 Slab Section Design

Input : L, L_n, f_c', w_{LL}, w_{SDL} (*not include self-weight), Exposure Condition, and Controlled Condition.

Output : Section of slab that calculated from input and its drawing.



L : 3.5 m

f'c : 28 MPa

wLL : 5.8 kN/m

wSDL*: 3 kN/m

*ไม่รวม self-weight

Exposure Condition: Exposed / Not exposed

Figure 1 Input window of Beam design

(Design sectional at maximum moment)

4.4 Guide for using Software

This software is user-friendly. It can easily use, start from; 1) Choose member that will be design; 2) Input information that required (window example shows in Fig. 1); 3) Wait for processing (take no longer than 1 min.); 4) Print-out the result (window example show in Fig. 2; print-out will be .xlsm file type); 5) The result file must be Save As before edit any data

4.5 Prominent points of Software

1) Able to select type of member (Beam and Slab)
2) Able to design at maximum moment or any section
3) Able to select exposure condition
4) Able to show short and full result

5) Conclusion

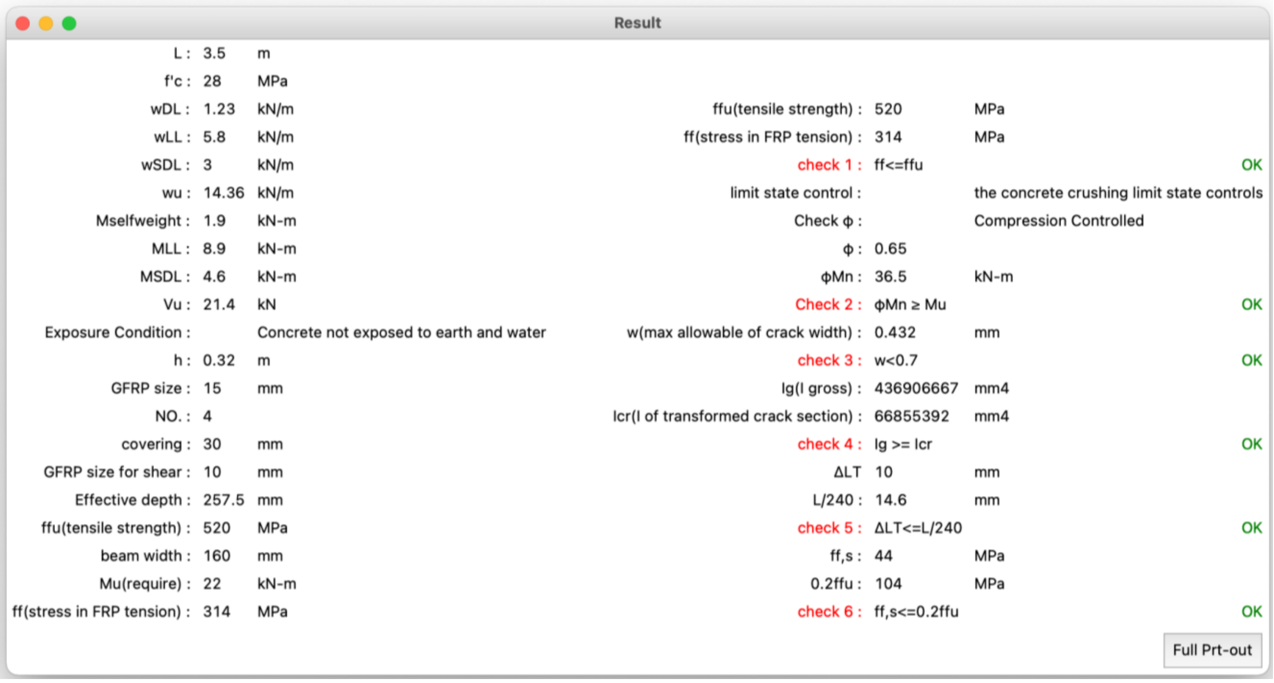
From project objectives, this program helps design cross-sectional of slabs and beams reinforced with GFRP rebars easier, decrease mistakes because of the precise process, and increase accuracy from computer calculations. Furthermore, this program can be a one of an alternative choice for using GFRP rebars as a material.

5.1. Advantages of program

1) User-friendly
2) Decrease designing time and increase accuracy
3) Design proper section of member and GFRP size
4) Have full and short calculations
5) Have sectional drawing
6) Be one of alternative programs for designer

5.2. Suggestions

1) Develop more alternative data for FRP rebars
2) Develop the program to be an application in smartphone
3) Add more types of supports which the program can design



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                      L :  3.5     m
                    f'c :  28      MPa
                    wDL :  1.23    kN/m                                          ffu(tensile strength) :  520        MPa
                    wLL :  5.8     kN/m                                     ff(stress in FRP tension) :  314        MPa
                   wSDL :  3       kN/m                                                     check 1 :  ff<=ffu                                   OK
                     wu :  14.36   kN/m                                          limit state control :             the concrete crushing limit state controls
            Mselfweight :  1.9     kN-m                                                     Check ϕ :             Compression Controlled
                    MLL :  8.9     kN-m                                                           ϕ :  0.65
                   MSDL :  4.6     kN-m                                                         ϕMn :  36.5       kN-m
                     Vu :  21.4    kN                                                       Check 2 :  ϕMn ≥ Mu                                  OK
     Exposure Condition :          Concrete not exposed to earth and water   w(max allowable of crack width) :  0.432  mm
                      h :  0.32    m                                                        check 3 :  w<0.7                                     OK
              GFRP size :  15      mm                                                 Ig(I gross) :  436906667  mm4
                    NO. :  4                                      Icr(I of transformed crack section) :  66855392   mm4
               covering :  30      mm                                                       check 4 :  Ig >= Icr                                 OK
     GFRP size for shear :  10      mm                                                          ΔLT   10         mm
         Effective depth :  257.5   mm                                                       L/240 :  14.6       mm
   ffu(tensile strength) :  520     MPa                                                     check 5 :  ΔLT<=L/240                                OK
              beam width :  160     mm                                                        ff,s :  44         MPa
             Mu(require) :  22      kN-m                                                    0.2ffu :  104        MPa
ff(stress in FRP tension) :  314     MPa                                                     check 6 :  ff,s<=0.2ffu                              OK
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Figure 2 Result window of Beam design (Design sectional at maximum moment)

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