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Thickness of Glass Fiber-Reinforced Polymer-Reinforced Concrete Slabs

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This paper proposes a relationship between the minimum thickness of glass fiber-reinforced polymer-reinforced concrete (GFRP-RC) solid non-prestressed one-way slabs and clear span. In total, 68 slabs were analyzed and designed using ACI CODE-440.11-22 addressing strength, serviceability, and detailing criteria. Slabs were analyzed with four end conditions: simply supported, one-end continuous, both-ends continuous, and cantilever. Based on the analysis and design, a relationship similar to the one given in ACI 318-19, Table 7.3.1.1, was proposed to provide designers with a way to avoid tedious calculations for the deflection of GFRP-RC slabs. It was observed that, irrespective of using maximum or minimum reinforcement limits, minimum slab thickness values were always lower for GFRP-RC slabs than conventional steel-RC slabs. Hence, using Table 7.3.1.1 in ACI 318-19 for the calculation of minimum slab thickness of GFRP-RC slabs will be conservative when the concrete strength is 4000 psi (28 MPa) or more and the deflection limit is $1/240$.

Keywords: deflection; glass fiber-reinforced polymer (GFRP) reinforcement; reinforced concrete (RC) slabs; thickness.

INTRODUCTION

The bulk of glass fiber-reinforced polymer (GFRP) reinforcement, including other fiber types such as carbon and basalt, has found its applications in transportation¹ but has seen limited use in buildings. A possible reason for this limitation is the lack of engineering design standards, but recent developments in material specifications and new construction strategies allow the exploitation of the full potential of this composite material.^{2,3} The ACI CODE-440.11-22⁴ Building Code for GFRP-reinforced concrete (GFRP-RC) members was recently published, which represents a critical aid to practitioners interested in the use of nonmetallic reinforcement in buildings.

The publication of ACI CODE-440.11-22⁴ is a stepping stone towards extensive use of composites in the building industry. However, owing to the novelty of GFRP-RC, ACI CODE-440.11-22⁴ is silent on some instances which are otherwise addressed in ACI 318-19⁵ for steel RC members. For example, ACI 318-19⁵ provides a relationship between minimum thickness of solid nonprestressed one-way slabs and clear span that satisfies deflection limits; however, ACI CODE-440.11-22⁴ is silent on this topic. This paper is an attempt to address this gap and to propose a span-to-thickness relation for GFRP-RC slabs based on the design provisions of ACI CODE-440.11-22.⁴

RESEARCH SIGNIFICANCE

The recently published ACI CODE-440.11-22⁴ does not provide any explicit relationship between span and thickness of GFRP-RC slabs. Therefore, a relation between minimum thickness and clear span would aid designers in avoiding tedious deflection calculations, which can be time-consuming. This study is carried out to investigate this topic with the objective of proposing provisions similar to the ones given in ACI 318-19, Section 7.3.1.1.⁵

METHODOLOGY

In this study, four types of one-way GFRP-RC slabs were designed based on different support conditions: simply supported, both-ends continuous, one-end continuous, and cantilever. The constituent materials selected for slab design are listed in Table 1. The concrete strength f'_c assumed was 4000 psi (28 MPa), and the GFRP type included both high-modulus bars ($E_f = 8700$ ksi [60,000 MPa]) as currently available in marketplace and Code-specified low-modulus bars ($E_f = 6500$ ksi [44,816 MPa]) compliant with material specification ASTM D7957.⁶

In this study, three nominal bar sizes were used as shown in Table 1. The mechanical properties of GFRP bars affecting design include guaranteed ultimate tensile strength f_{fu} , the corresponding ultimate strain ϵ_{fu} , modulus of elasticity E_f , and modular ratio n_f . A value of 1.20 for the bond coefficient, k_b , and 0.85 for the environmental reduction factor, C_e , were adopted as indicated in ACI CODE-440.11-22,⁴ Sections 24.3.2.3 and 20.2.2.3, respectively. A concrete cover of 0.75 in. (19 mm) was used as specified in ACI CODE-440.11-22,⁴ Section 20.5.1.3.1.

The slabs were designed as over-reinforced in the first phase (that is, providing as much GFRP reinforcement as permitted by ACI CODE-440.11-22) and using minimum reinforcement in the second phase, indicated in ACI CODE-440.11-22,⁴ Section 7.6.1.1

$$A_{fmin} = \frac{300}{f_{fu}} A_g \quad (1)$$

The third phase of this study involved developing a relationship between the clear span and minimum thickness of non-prestressed one-way slabs based on the outcomes of the

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Table 1—Properties of GFRP reinforcement as per ASTM D7957⁶

Designation and Bar No.	Diameter, in.	Area, in. ²	Elastic modulus, ksi	Guaranteed tensile strength, ksi	Ultimate strain, %	Concrete strength, psi	Concrete clear cover, in.
GFRP-04*	0.50	0.20	8700	139.5	0.016	4000	0.75
GFRP-05*	0.62	0.31		131.6	0.015		
GFRP-06*	0.75	0.44		130.2	0.015		
GFRP-04	0.50	0.20	6500	108.0	0.016		
GFRP-05	0.62	0.31		94.0	0.014		
GFRP-06	0.75	0.44		93.0	0.014		

*New-generation bars with higher modulus of elasticity and guaranteed strength as proposed in ASTM material specification under development.

Note: 1 in. = 25.4 mm; 1 in.² = 645 mm²; 1 ksi = 6.89 MPa; 1 psi = 0.00689 MPa.

first two phases. The analysis and design were carried out with Mathcad spreadsheets specifically developed for the design of GFRP-RC slabs. As an example, schematic dimensions and reinforcement details of a continuous GFRP-RC slab are given in Fig. 1. The details about reinforcement are given later in the paper.

ANALYSIS AND DESIGN

The slabs were designed at a superimposed dead load of 10 lb/ft² (0.48 kN/m²) and a live load of 40 lb/ft² (1.92 kN/m²) as indicted in Table 4.3-1 of ASCE 7-16.⁷ These loads are typical of a residential building and were combined as per ASCE 7-16.⁷ Maximum factored moments and shear forces were determined using a simplified method of analysis for continuous one-way slabs as per ACI CODE-440.11-22, Section 6.5.⁴ The approximate moment values were calculated by the relations given in the Table 2 as per ACI CODE-440.11-22.⁴

For applicable load combinations, the slab unit strip was designed to satisfy the requirements of ACI CODE-440.11-22, Sections 7.5.1.1(a) and 7.5.1.1(b)⁴

$$\Phi M_n \geq M_u \quad (2)$$

$$\Phi V_n \geq V_u \quad (3)$$

Strength-reduction factors used in the design were calculated as per ACI CODE-440.11-22,⁴ Sections 21.2.1 and 21.2.2, given in Tables 3 and 4, respectively. The maximum spacing of GFRP reinforcement was limited as specified by ACI CODE-440.11-22,⁴ Eq. (24.3.2a) and (24.3.2b)

$$S \leq \frac{0.032 E_f}{f_{fs} k_b} - 2.5 c_c \text{ (U.S. units)} \quad (4)$$

$$S \leq \frac{0.81 E_f}{f_{fs} k_b} - 2.5 c_c \text{ (SI units)}$$

$$S \leq 0.026 \frac{E_f}{f_{fs} k_b} \text{ (U.S. units)} \quad (5)$$

$$S \leq 0.66 \frac{E_f}{f_{fs} k_b} \text{ (SI units)}$$

Maximum permissible deflection limits were calculated as per ACI CODE-440.11-22,⁴ Section 24.2.2, assuming slabs

not supporting or attached to partitions or other non-structural elements are likely to be damaged by large deflections. The limit was used to make this study analogous to one carried out in ACI 318-19⁵ to develop a relationship between thickness of slabs with clear span.

$$\Delta = l/240 \quad (6)$$

If the slabs were to be attached to structural members likely to be damaged by large deflection ($\Delta = l/340$), the relations developed in this study would not be conservative.

Strength requirements

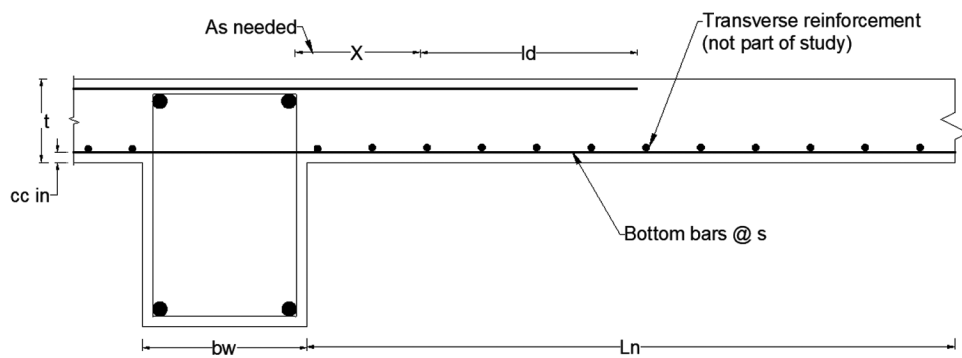
Flexural strength—The high strength of GFRP bars allows the design to satisfy flexural requirements at low reinforcement ratios. However, the slab cross sections were designed with maximum reinforcement in phase 1 to offset the effect of the lower elastic modulus of GFRP bars. As a result, stresses in the GFRP bars were significantly less than the ultimate guaranteed tensile strength f_{tu} .

Figure 2 shows the strain distribution in a simply supported slab having a clear span of 16 ft (4.9 m). The slab required a thickness of 6 in. (153 mm) at maximum reinforcement allowed by the ACI CODE-440.11-22,⁴ provided at 2.5 in. (64 mm) center-to-center, as shown in Table 5. Because the slab was designed at maximum reinforcement, the strain in the GFRP reinforcement is lower than its ultimate value. In Fig. 2, ϵ_f is the strain in the reinforcement at corresponding c_u (neutral axis depth) and ϵ_{cu} is the maximum strain in the concrete. This slab unit-strip was designed for a factored moment of 5.3 kip-ft/ft (7.1 kN-m) and a shear force of 1.3 kip (5.8 kN). The design strength of the slab unit-strip was 22 kip-ft/ft (29.8 kN-m) and the shear strength provided by concrete was 3.3 kip/ft (33 kN/m).

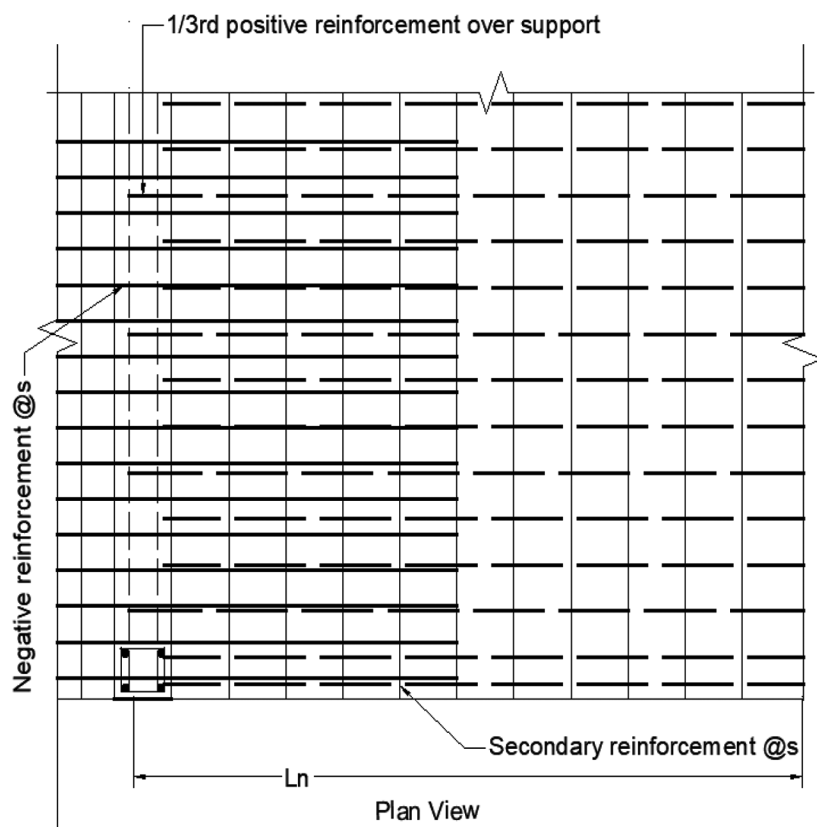
In phase 2, the design of each slab type was started with minimum GFRP flexural reinforcement as given in ACI CODE-440.11-22, Section 7.6.1.1,⁴ and reinforcement was adjusted based on the maximum bar spacing limitation imposed by the Code. At times, this resulted in a compression-controlled failure.

Shear strength—The nominal shear strength of slab was calculated as per ACI CODE-440.11-22, Section 22.5.1.1⁴

$$V_n = V_c + V_f \quad (7)$$



Longitudinal reinforcement details



Plan View

Fig. 1—Schematic dimensions and reinforcement details of continuous slab.

Table 2—Approximate moments for one-way slabs (ACI 440.11-22,⁴ Table 6.5.2)

Moment	Location	Condition	M_u
Positive	Endspan	Discontinuous end integral with support	$W_u l_n^2/14$
		Discontinuous end unrestrained	$W_u l_n^2/11$
	Interior spans	All	$W_u l_n^2/16$
Negative	Interior face of exterior support	Members built integrally with supporting spandrel beam	$W_u l_n^2/24$
		Members built integrally with supporting column	$W_u l_n^2/16$
	Exterior face of first interior support	Two spans	$W_u l_n^2/9$
		More than two spans	$W_u l_n^2/10$
	Face of other supports	All	$W_u l_n^2/11$

The shear strength provided by concrete section was calculated as the greater of two expressions from ACI CODE-440.11-22, Sections 22.5.5.1a and 22.5.5.1b⁴

$$V_c = 5\lambda k_{cr} \sqrt{f'_c} bd \text{ (U.S. units)}$$

$$V_c = 0.42\lambda k_{cr} \sqrt{f'_c} bd \text{ (SI units)}$$
(8)

Table 3—Strength reduction factor Φ (ACI CODE-440.11-22,⁴ Section 21.2.1)

Action or structural element	Φ
Moment, axial force, or combined axial moment and axial force	0.55 to 0.65 in accordance with 21.2.2
Shear	0.75

Table 4—Strength reduction factor Φ for moment, axial force, or combined moment and axial force (ACI CODE-440.11-22,⁴ Section 21.2.2)

Net tensile strain at failure in outermost layer of GFRP reinforcement ϵ_f	Classification	Φ
$\epsilon_f = \epsilon_{fu}$	Tension-controlled	0.55
$\epsilon_{fu} > \epsilon_f > 0.8\epsilon_{fu}$	Transition	1.05 to $0.5\epsilon_f/\epsilon_{fu}$
$\epsilon_f \leq 0.8\epsilon_{fu}$	Compression-controlled	0.65

Table 5—Simply supported slabs with $E_f = 8700$ ksi (1260 MPa) at maximum reinforcement

Clear span, ft	Thickness, in.	Bar size with center-to-center spacing			Required area, in. ²	Provided area*, in. ²
F-11	4	No. 4 @ 6.5	No. 5 @ 9.5	No. 6 @ 11	0.14	0.36
F-12	5	No. 4 @ 7.5	No. 5 @ 9.5	No. 6 @ 11.5	0.16	0.31
F-13	5	No. 4 @ 6.5	No. 5 @ 8.5	No. 6 @ 10.5	0.16	0.36
F-14	5	—	No. 5 @ 4	No. 6 @ 5.5	0.16	0.94
F-15	6	No. 4 @ 5	No. 5 @ 8	No. 6 @ 9	0.20	0.47
F-16	6	—	No. 5 @ 4	No. 6 @ 5.5	0.20	0.94
F-17	7	No. 4 @ 4	No. 5 @ 6	No. 6 @ 9	0.24	0.59

*Provided reinforcement area was calculated based on No. 4 (M13) bars; when not shown, it is because center-to-center spacing is less than 3 in. (75 mm).

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

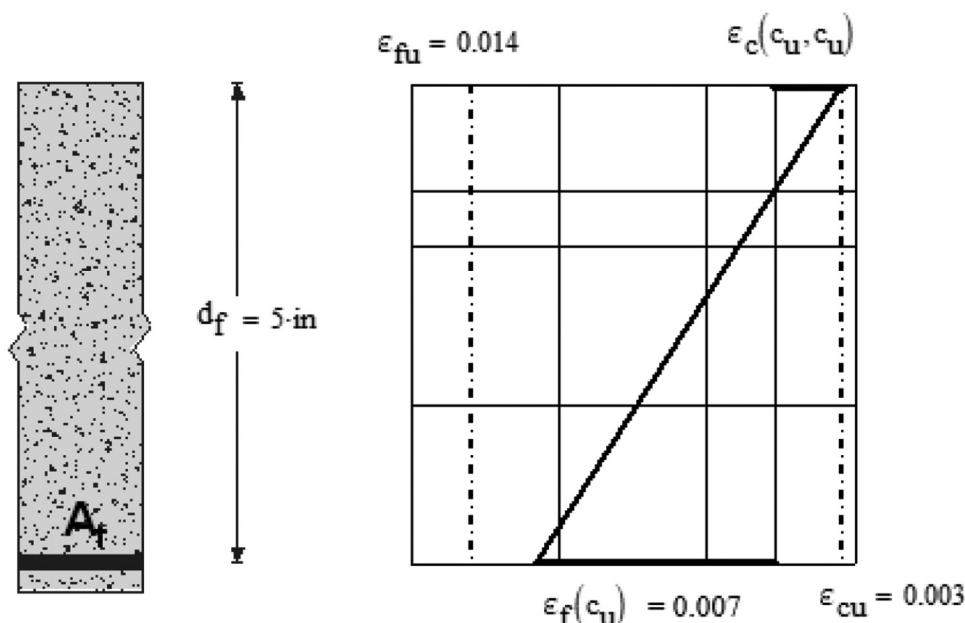


Fig. 2—Stress and strain distribution in 6 in. (153 mm) simply supported slab. (Note: 1 in. = 25.4 mm.)

neutral axis depth to the effective depth (k_{cr}), reinforcement ratio (ρ), and modular ratio (n_f) were calculated as per ACI CODE-440.11-22, Eq. (R22.5.5.1a) and (R22.5.5.1b) and Section R22.5.5.1, respectively

$$k_{cr,rect} = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \quad (11)$$

$$\rho_f = A_f / b_w d \quad (12)$$

$$n_f = E_f / E_c \quad (13)$$

For all cases considered in this study, the design shear strength provided by concrete was always greater than the ultimate shear force calculated by analysis. Hence, no shear reinforcement was provided.

Detailing and serviceability requirements (simply supported slabs)

In GFRP-RC slab design, deflection often controls due to the lower elastic modulus of GFRP bars compared to steel. Hence, more reinforcement or thicker slabs compared to steel-RC slabs are required to offset this. Therefore, in the first phase of the study, the slab cross sections were designed as compression-controlled using the maximum reinforcement to control the deflection with the minimum slab thickness, whereas, in the second phase, slab thickness was increased while keeping the reinforcement at a minimum. The amount of GFRP reinforcement to satisfy strength requirement is indicated as a “required area,” whereas the larger amount of GFRP reinforcement needed to satisfy serviceability requirements (that is, deflection control) and detailing requirements (that is, maximum bar spacing) is indicated as “provided area.”

The difference between required and provided areas of reinforcement to meet any strength, serviceability, and detailing requirements can be observed in Table 5, developed for the cases of simply supported slabs using high-modulus ($E_f = 8700$ ksi [60,000 MPa]) GFRP bars. For example, in the slab with a clear span of 15 ft (4.6 m) (F-15), the required reinforcement area to meet strength is 0.21 in.^2 (135 mm^2), while the provided area using No. 4 bar is 0.47 in.^2 (303 mm^2) to also meet serviceability. For slabs F-11 to F-13, the required area was sufficient to meet serviceability requirements,

but had to be increased to the provided value due to the maximum spacing limitation of ACI CODE-440.11-22.⁴

In the second phase of the study, reinforcement was kept at minimum and serviceability was controlled by increasing the slab thickness. In Table 6, the overall required thickness increased compared to the values listed in Table 5, when slabs were designed at minimum reinforcement. For example, a slab with a clear span of 15 ft (4.6 m) (F-15) in Table 6 required a thickness value of 7 in. (175 mm), whereas the same span required a thickness of 6 in. (153 mm) when designed at maximum reinforcement. It may be noted in Table 6 that the provided area is always greater than minimum required area. Again, this is because of ACI CODE-440.11-22⁴ requirements for maximum spacing. For example, the required reinforcement area for F-15 to meet strength is 0.21 in.^2 (135 mm^2), while the provided area using No. 4 bar is 0.39 in.^2 (251 mm^2), and with No. 6 bar, it increases to 0.59 in.^2 (381 mm^2). Meeting the maximum bar spacing limit also changed the failure mode from tension to compression.

The study also included analysis and design of GFRP bars having low elastic modulus ($E_f = 6500$ ksi [44,816 MPa]) as per ASTM D7957-22.⁶ The slabs required more reinforcement compared to new-generation bars of higher modulus, as shown in Table 7, for the case of maximum reinforcement and minimum thickness. For example, the slab with a clear span of 15 ft (4.6 m) (F-15) in Table 7 required a thickness of 6 in. (153 mm), which is the same as for clear span in Table 5, but the provided area was increased to 0.59 in.^2 (381 mm^2).

The effect of using maximum and minimum reinforcement with bars of different elastic moduli on the design thickness of simply supported one-way slabs as a function of clear span can be graphically observed in Fig. 3. GFRP bars of low elastic modulus required more slab thickness or reinforcement area than new-generation bars.

Also shown is the line of the proposed equation that can be used to find the preliminary thickness of simply supported slabs without detailed deflection calculations. This equation yields the following value for minimum slab thickness

$$h = l/22 \quad (14)$$

where l is in in. (mm).

Table 6—Simply supported slabs with $E_f = 8700$ ksi (60,000 MPa) at minimum reinforcement

Clear span, ft	Thickness, in.	Bar size with center-to-center spacing			Required area, in. ²	Provided area,* in. ²	Failure mode
F-11	5	No. 4 @ 8	No. 5 @ 10	No. 6 @ 12	0.16	0.29	Compression-controlled
F-12	5	No. 4 @ 7.5	No. 5 @ 9.5	No. 6 @ 11	0.16	0.31	
F-13	6	No. 4 @ 7	No. 5 @ 9	No. 6 @ 11	0.18	0.34	
F-14	6	No. 4 @ 7	No. 5 @ 8.5	No. 6 @ 10	0.18	0.34	
F-15	7	No. 4 @ 6	No. 5 @ 8	No. 6 @ 9	0.21	0.39	
F-16	7	No. 4 @ 6	No. 5 @ 8	No. 6 @ 9	0.21	0.39	
F-17	8	No. 4 @ 6	No. 5 @ 7	No. 6 @ 9	0.25	0.39	

*Provided reinforcement area was calculated based on No. 4 (M13) bars; when not shown, it is because center-to-center spacing is less than 3 in. (75 mm).

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

Table 7—Simply supported slabs with $E_f = 6500$ ksi (44,816 MPa) at maximum reinforcement

Clear span, ft	Thickness, in.	Bar size with center-to-center spacing			Required area, in. ²	Provided area,* in. ²	Failure mode
F-11	4	No. 4 @ 5	No. 5 @ 7.5	No. 6 @ 9.5	0.16	0.47	Compression controlled
F-12	5	No. 4 @ 6.5	No. 5 @ 8	No. 6 @ 9.5	0.20	0.36	
F-13	5	No. 4 @ 4	No. 5 @ 7	No. 6 @ 9	0.20	0.59	
F-14	6	No. 4 @ 5	No. 5 @ 7.5	No. 6 @ 9	0.25	0.47	
F-15	6	No. 4 @ 4	No. 5 @ 6	No. 6 @ 8.5	0.25	0.59	
F-16	7	No. 4 @ 5	No. 5 @ 6.5	No. 6 @ 8	0.30	0.47	
F-17	7	No. 4 @ 3	No. 5 @ 4.5	No. 6 @ 605	0.30	0.79	

*Provided reinforcement area was calculated based on No. 4 (M13) bars; when not shown, it is because center-to-center spacing is less than 3 in. (75 mm).

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

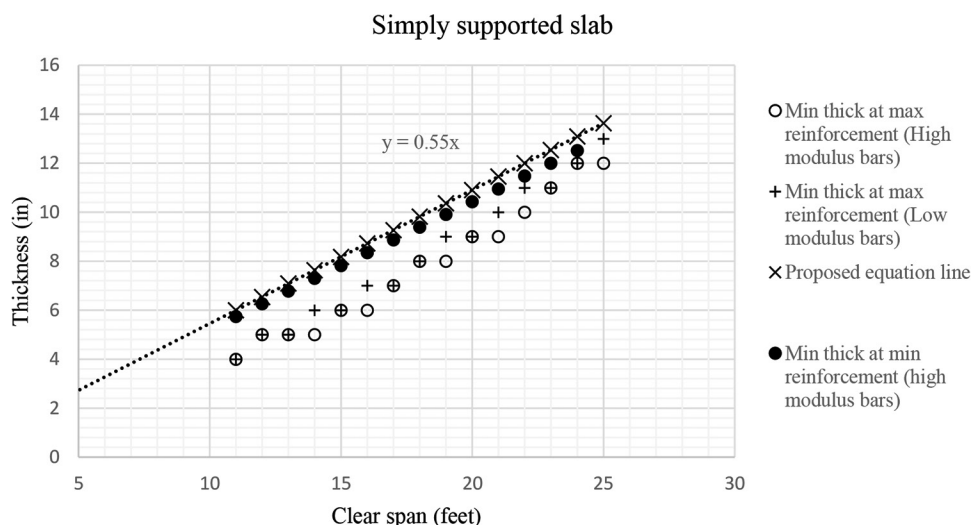


Fig. 3—Simply supported slabs with high- and low-modulus GFRP bars. (Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m.)

Detailing and serviceability requirements (continuous end slabs)

In the case of continuous slabs, for a given slab thickness, the negative reinforcement over the support was kept at the minimum amount to satisfy the strength (and detailing) requirements, while positive reinforcement was gradually increased to satisfy strength, serviceability, and detailing requirements. The impact of slab continuity on the effective moment of inertia of the slab unit-strip can be observed in Eq. (15) as provided in ACI CODE-440.11-22, Section 24.2.3.6,⁴ showing that the effective moment of inertia is the weighted average of values at three sections (ends and midspan)

$$I_e = 0.71I_{e+} + 0.15(I_{e1-} + I_{e2-}) \quad (15)$$

where I_e is the effective moment of inertia for the calculation of deflection in in.⁴ (mm⁴); I_{e+} is the effective moment of inertia at the location of a maximum positive moment for the calculation of deflection in in.⁴ (mm⁴); I_{e1-} is the effective moment of inertia at the location of a maximum negative moment at the near end of the span for calculation of deflection in in.⁴ (mm⁴); and I_{e2-} is the effective moment of inertia at the location of a maximum negative moment at the far end of the span for calculation of deflection in in.⁴ (mm⁴).

The decreased bending moment at the midspan in continuous slabs and the increased effective moment of inertia has a noticeable effect on the required slab thickness.

In the first phase, after defining the amount of negative reinforcement, positive reinforcement was increased to the maximum to satisfy strength, serviceability, and detailing requirements. Table 8 presents the results of slab design for the case of high modulus GFRP bars. For negative moments, the required area comes from strength need whereas the provided includes detailing requirements. The same is applicable to positive moments in which case the provided area also needs to satisfy serviceability. Comparing slab with a clear span of 15 ft (4.6 m) (F-15) for the case of simply supported (Table 5) and the corresponding one with both ends continuous (Table 8), the thickness reduced from 6 to 5 in. (153 to 127 mm) with the same amount of provided reinforcement No. 4 at 5 in. (127 mm) center-to-center.

In phase 2, reinforcement was initially kept at the ACI CODE-440.11-22⁴ required minimum along the entire span (required) but increased to meet detailing (while serviceability is met by increasing thickness). It can be observed in Table 9 that in using minimum reinforcement, required thickness values increased, compared to same clear spans in Table 8. The provided reinforcement area was affected by the maximum spacing limitations of ACI CODE-440.11-22.⁴

Table 8—Both-end continuous slabs at maximum reinforcement with $E_f = 8700$ ksi (60,000 MPa)

Clear span, ft	Thickness, in.	Negative reinforcement at each support provided			Required area, in. ²	Provided area,* in. ²	Positive reinforcement provided			Required area, in. ²	Provided area,* in. ²
F-11	4	No. 4 @ 9	No. 5 @ 11	No. 6 @ 14	0.12	0.26	No. 4 @ 9	No. 5 @ 11	No. 6 @ 14	0.14	0.26
F-12	4	No. 4 @ 8	No. 5 @ 10	No. 6 @ 12	0.12	0.29	No. 4 @ 8	No. 5 @ 10	No. 6 @ 12	0.14	0.29
F-13	4	No. 4 @ 7	No. 5 @ 9	No. 6 @ 11	0.12	0.34	No. 4 @ 5	No. 5 @ 7	No. 6 @ 11	0.14	0.47
F-14	5	No. 4 @ 7	No. 5 @ 9	No. 6 @ 11	0.16	0.34	No. 4 @ 9	No. 5 @ 11	No. 6 @ 14	0.16	0.26
F-15	5	No. 4 @ 7	No. 5 @ 9	No. 6 @ 10	0.16	0.34	No. 4 @ 5	No. 5 @ 8	No. 6 @ 12	0.16	0.47
F-16	5	No. 4 @ 6	No. 5 @ 8	No. 6 @ 10	0.16	0.39	—	No. 5 @ 4	No. 6 @ 6	0.16	0.94
F-17	6	No. 4 @ 6	No. 5 @ 8	No. 6 @ 10	0.20	0.39	No. 4 @ 4	No. 5 @ 7	No. 6 @ 10	0.20	0.59

*Provided reinforcement area was calculated based on No. 4 (M13) bars; when not shown, it is because center-to-center spacing is less than 3 in. (75 mm).

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

Table 9—Both-end continuous slabs at minimum reinforcement with $E_f = 8700$ ksi (60,000 MPa)

Clear span, ft	Thickness, in.	Negative reinforcement at each support provided			Required area, in. ²	Provided area,* in. ²	Positive reinforcement provided			Required area, in. ²	Provided area,* in. ²
F-11	4	No. 4 @ 9	No. 5 @ 12	No. 6 @ 12	0.12	0.26	No. 4 @ 11	No. 5 @ 11	No. 6 @ 13	0.12	0.21
F-12	4	No. 4 @ 8	No. 5 @ 10	No. 6 @ 12	0.12	0.29	No. 4 @ 10	No. 5 @ 12	No. 6 @ 14	0.12	0.24
F-13	5	No. 4 @ 8	No. 5 @ 10	No. 6 @ 12	0.15	0.29	No. 4 @ 10	No. 5 @ 12	No. 6 @ 15	0.15	0.24
F-14	5	No. 4 @ 7	No. 5 @ 9	No. 6 @ 11	0.15	0.34	No. 4 @ 9	No. 5 @ 11	No. 6 @ 14	0.15	0.26
F-15	6	No. 4 @ 7	No. 5 @ 9	No. 6 @ 11	0.18	0.34	No. 4 @ 8	No. 5 @ 11	No. 6 @ 13	0.18	0.29
F-16	6	No. 4 @ 7	No. 5 @ 9	No. 6 @ 10	0.18	0.34	No. 4 @ 8	No. 5 @ 10	No. 6 @ 12	0.18	0.29
F-17	7	No. 4 @ 7	No. 5 @ 8	No. 6 @ 10	0.21	0.34	No. 4 @ 8	No. 5 @ 9	No. 6 @ 12	0.21	0.29

*Provided reinforcement area was calculated based on No. 4 (M13) bars; when not shown, it is because center-to-center spacing is less than 3 in. (75 mm).

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

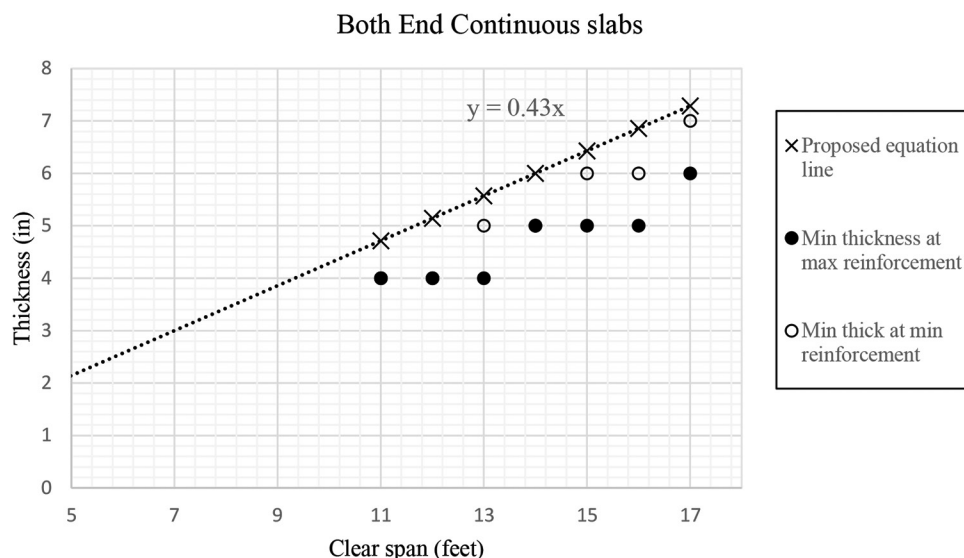


Fig. 4—Both-end continuous slabs with high-modulus GFRP bars. (Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m.)

It was further noted that using minimum or maximum reinforcement did not leave a significant effect on required slab thickness; this is due to additional reinforcement area provided because of maximum spacing limitations. As can be seen in Table 9, for a 15 ft (4.6 m) slab (F-15), minimum reinforcement required and provided at midspan are 0.18 and 0.26 in.² (116 and 187 mm²), respectively, with a 6 in. (153 mm) slab thickness. The corresponding slab in Table 8 shows that required and provided reinforcement area at

midspan are 0.16 and 0.47 in.² (103 and 303 mm²), respectively, with a 5 in. (127 mm) slab thickness.

The effect of maximum and minimum reinforcement on the thickness of slabs is graphically shown in Fig. 4, along with the line of proposed equation to calculate minimum thickness of both end continuous GFRP-RC slabs. The equation yields the following value for minimum slab thickness

$$h = l/28 \quad (16)$$

Table 10—One-end continuous slab with $E_f = 8700$ ksi (60,000 MPa) at minimum reinforcement

Clear span, ft	Thickness, in.	Negative reinforcement provided						Positive reinforcement provided	Required area, in. ²	Provided area, in. ²
		Interior face of exterior support	Required area, in. ²	Provided area, in. ²	Exterior face of interior support	Required area, in. ²	Provided area, in. ²			
F-11	4	No. 4 @ 10	0.12	0.24	No. 4 @ 5	0.12	0.47	No. 4 @ 10	0.12	0.24
F-12	4	No. 4 @ 10	0.12	0.24	No. 4 @ 5	0.12	0.47	No. 4 @ 9	0.12	0.26
F-13	5	No. 4 @ 10	0.15	0.24	No. 4 @ 5	0.15	0.47	No. 4 @ 9	0.15	0.26
F-14	5	No. 4 @ 9	0.15	0.26	No. 4 @ 5	0.15	0.47	No. 4 @ 8	0.15	0.29
F-15	6	No. 4 @ 8	0.18	0.29	No. 4 @ 4	0.18	0.59	No. 4 @ 8	0.18	0.29
F-16	6	No. 4 @ 8	0.18	0.29	No. 4 @ 4	0.18	0.59	No. 4 @ 8	0.18	0.29
F-17	7	No. 4 @ 8	0.21	0.29	No. 4 @ 4	0.21	0.59	No. 4 @ 8	0.21	0.29

*Provided reinforcement area was calculated based on No. 4 (M13) bars; when not shown, it is because center-to-center spacing is less than 3 in. (75 mm).

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

where l is in in. (mm).

There was no significant difference between moment values at midspan for one-end continuous slabs and both-end continuous slabs. Additionally, required reinforcement was mostly controlled by the minimum reinforcement area specified by ACI CODE-440.11-22.⁴ Therefore, the required thickness values for one-end continuous slabs were similar to the ones for both-end continuous slabs. The only difference between the two cases is in the provided area of reinforcement at the exterior face of the interior support, where due to higher moment values, spacing limitations become more severe. Hence, the provided area of reinforcement was higher. The required and provided reinforcement areas at three locations along the slab unit strip and required thickness values for one-end continuous slabs are provided in Table 10.

Detailing and serviceability requirements (cantilever)

A different trend was observed in the design of cantilever slabs. Starting with a clear span of 4 ft (1.2 m), with every foot (meter) of increase in the length, a significant increase in thickness was required to satisfy the deflection limit of $l/240$. The use of maximum reinforcement possible did not help, and deflection was ultimately governed by the slab thickness. Therefore, as shown in Table 11 and Fig. 5, the required thickness increases linearly with span. Also, in Fig. 5, a line for the proposed equation is shown to find preliminary thickness of cantilever slabs. The equation yields the following value for minimum slab thickness

$$h = l/12 \quad (17)$$

where l is in in. (mm).

Maximum spacing limitations

The spacing of GFRP reinforcement is limited to control cracking using a procedure developed by Ospina and Bakis⁸ based on the modification to the work done by Frosch for steel-reinforced concrete which was carried out in 1999.⁹ The maximum spacing of GFRP reinforcement was calculated using the equation given in ACI CODE-440.11-22,

Sections 24.3.2a and 24.3.2b.⁴ For example, in both-end continuous slabs at a span of 15 ft (4.6 m) (F-15), in Table 9, the spacing was calculated as follows: $E_f = 8700$ ksi (60,000 MPa); $M_s = 2.0$ kip-ft (2.7 kN-m)—moment at service loads; $A_f = 0.26$ in.² (168 mm²)—reinforcement area provided; $d_f = 5$ in. (127 mm)—depth from compression fiber to center of tensile reinforcement; and $k_{cr} = 0.14$ —ratio of cracked transformed section neutral axis depth to effective depth.

Stresses in the reinforcement at service loads are calculated using the following equation

$$f_{fs} = \frac{M_s}{A_f d_f \left(1 - \frac{k_{cr}}{3}\right)} = 19.2 \text{ ksi (134 MPa)}$$

$$k_b = 1.20$$

$$S \leq \frac{0.032 \times 8700}{19.2 \times 1.20} - 2.5 \times 0.75 = 10.3 \text{ in. (262 mm)}$$

$$S \leq 0.026 \times \frac{8700}{19.2 \times 1.20} = 9.8 \text{ in. (249 mm)}$$

where $S_{max} = \min(10.3, 9.8) = 9.8$ in. (249 mm).

The required area of reinforcement is 0.18 in.² (116 mm²) and the provided area using No. 4 (M13) bar is 0.26 in.² (168 mm²). The extra 0.08 in.²/ft is used because reinforcing bars could not space beyond 9.8 in. (249 mm) due to Code limitations. There has been improvement in material properties, and the use of significant extra reinforcement makes this limit debatable.

Relationship between thickness and clear span

In simplified design and particularly for pre-dimensioning, the slab thickness (depth) is usually determined in relation to its clear span for typical building geometries as given in ACI 318-19, Table 7.3.1.1,⁵ but no such relations are provided for the design of slabs using GFRP reinforcement in ACI CODE-440.11-22.⁴ In this study, relations between thickness and clear span of slabs were developed based on the data obtained from the design of slabs with four different end conditions and are given in Table 12. These ratios are applicable for design with new generation high modulus

Table 11—Cantilever slabs with $E_f = 8700$ ksi (60,000 MPa) at maximum reinforcement

Clear span, ft	Thickness, in.	Reinforcement provided			Required area, in. ²	Provided area,* in. ²
F-04	4	No. 4 @ 10	No. 5 @ 13	No. 6 @ 15	0.12	0.24
F-05	4	No. 4 @ 7	No. 5 @ 8	No. 6 @ 10.5	0.12	0.34
F-06	5	No. 4 @ 6.5	No. 5 @ 8	No. 6 @ 9.5	0.14	0.36
F-07	6	No. 4 @ 5.5	No. 5 @ 7.5	No. 6 @ 9	0.17	0.43

*Provided reinforcement area was calculated based on No. 4 (M13) bars.

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; in bar sizes, No. 4 = M13, 5 = M16, and 6 = M19.

Table 12—Minimum thickness of solid non-prestressed one-way slabs for GFRP- and steel-RC

Support condition	GFRP-RC h , in. (A_{fmax})	GFRP-RC h , in. (A_{fmin})	Steel-RC h , in. (ACI 318-19)
Simply supported	$l/24$	$l/22$	$l/20$
Both-ends continuous	$l/30$	$l/28$	$l/28$
One-end continuous	$l/30$	$l/28$	$l/24$
Cantilever	$l/13$	$l/12$	$l/10$

Note: 1 in. = 25.4 mm.

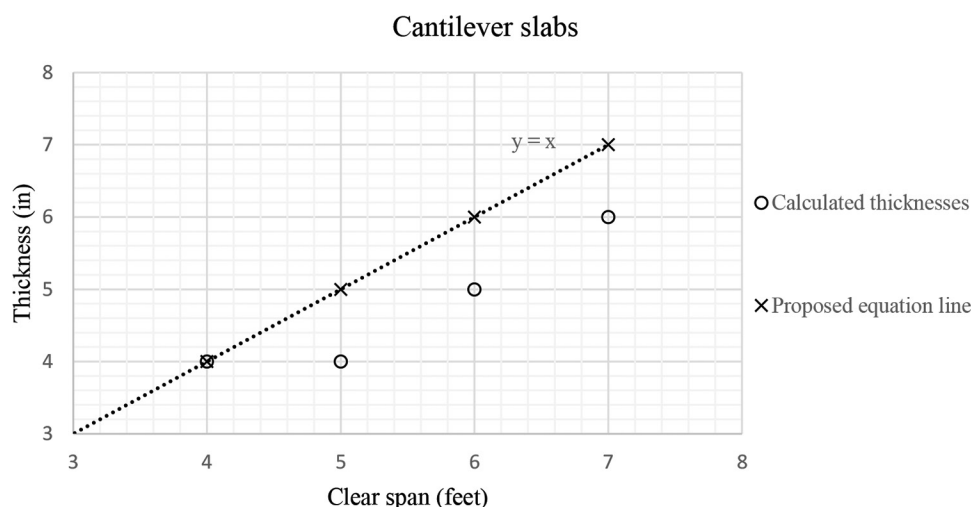


Fig. 5—Cantilever slabs with high-modulus GFRP bars. (Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m.)

bars or lower modulus bars complying with ASTM D7957.⁶ The relations are limited to a maximum clear span of 20 ft (6.1 m) for continuous and simply supported slabs. The ratios presented in Table 12 satisfy all the requirements of strength, serviceability, and detailing. It can be observed that the ratios given in this table for GFRP-RC one-way solid non-prestressed slabs result in lower thickness values compared to relations given in the ACI 318-19 Code.⁵ The reason for this unexpected outcome is because of the provisions of ACI CODE-440.11-22⁴ result in significantly larger reinforcement ratios when compared to steel.

To test this hypothesis, a concrete strength of 2000 psi (14 MPa) and minimum GFRP reinforcement for strength without considering spacing limitations was considered. In this case, slab thickness values of GFRP-RC were higher than in the case of steel-RC. It is possible that the depth-to-span relationships in ACI 318-19⁵ may have been developed with concrete strength lower than 4000 psi (28 MPa).

CONCLUSIONS AND RECOMMENDATIONS

In this study, 68 one-way glass fiber-reinforced polymer-reinforced concrete (GFRP-RC) slabs with four end-conditions were designed as per ACI CODE-440.11-22.⁴ A relationship between minimum thickness and clear span was investigated using both high-modulus ($E_f = 8700$ ksi [60,000 MPa]) and low-modulus ($E_f = 6500$ ksi [44,816 MPa]) GFRP bars. The concrete strength f'_c assumed was 4000 psi (28 MPa) and bond coefficient $k_b = 1.20$, per ACI CODE-440.11-22,⁴ was used. Other assumptions related to applied load (for example, residential buildings) and maximum permissible deflection limit of $l/240$ were also made.

Based on the outcomes of this study, the following conclusions were drawn:

1. Design of slabs reinforced with GFRP is generally governed by serviceability (that is, deflection control) and detailing (that is, maximum reinforcement spacing).
2. Given the lower modulus of elasticity of GFRP bars, a higher reinforcement ratio is needed to satisfy deflec-

tion limits, and consequently more bars are required for GFRP-RC slabs.

3. Recent developments in the manufacturing of GFRP bars and increased modulus of elasticity from 6500 to 8700 ksi (44,816 to 60,000 MPa) impact slab design. The proposed relations between minimum thickness and clear span of this study are applicable to the design of GFRP-RC slabs with both high- and low-modulus GFRP bars.

4. The proposed relations for minimum thickness of solid non-prestressed one-way slabs satisfies all design requirements (that is, strength, serviceability, and detailing) as per ACI CODE-440.11-22.⁴

5. The proposed relations are applicable to a maximum clear span of 20 ft (6.1 m) for simply supported and continuous slabs.

6. Minimum thickness values obtained for solid non-prestressed one-way GFRP-RC slabs were all lower than those with steel reinforcement. Hence, using the same relations as given in ACI 318-19, Table 7.3.1.1 will always be conservative.

7. The proposed relations will be conservative when the concrete strength is 4000 psi (28 MPa) or more and the deflection limit is $l/240$.

8. It is suggested to use small-diameter bars to avoid providing more reinforcement area due to spacing limitations of the Code. However, large-diameter bars may result in savings in labor cost.

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NOTATION AND TERMINOLOGY

A_f	=	reinforcement area provided
A_{fmin}	=	minimum area of GFRP reinforcement, in. ² (mm ²)
A_g	=	gross area of concrete section, in. ² (mm ²)
c_c	=	concrete cover

d_f	=	depth from extreme compression fiber to center of tensile reinforcement
E_f	=	modulus of elasticity of GFRP reinforcement, psi (MPa)
f_{fs}	=	tensile stress in GFRP reinforcement at service loads, psi (MPa)
f_{fu}	=	guaranteed tensile strength of GFRP longitudinal reinforcement, psi (MPa)
I_e	=	effective moment of inertia for calculation of deflection, in. ⁴ (mm ⁴)
I_{e+}	=	effective moment of inertia at location of maximum positive moment for calculation of deflection in. ⁴ (mm ⁴)
I_{e1-}	=	effective moment of inertia at location of maximum negative moment at near end of span for calculation of deflection, in. ⁴ (mm ⁴)
I_{e2-}	=	effective moment of inertia at location of maximum negative moment at far end of span for calculation of deflection, in. ⁴ (mm ⁴)
k_b	=	bond coefficient
k_{cr}	=	ratio of cracked transformed section neutral axis depth to effective depth
l_n	=	length of clear span measured face-to-face of supports, in. (mm)
M_n	=	nominal moment at section, in.-lb (m-kN)
M_s	=	moment at service load, in.-lb (m-kN)
M_u	=	ultimate factored moment at section, in.-lb (m-kN)
n_f	=	modular ratio
S	=	center-to-center spacing, in. (mm)
S_{max}	=	maximum allowed spacing, in. (mm)
V_c	=	shear strength provided by concrete section
V_f	=	shear strength provided by shear reinforcement
V_n	=	nominal shear strength, kip (kN)
V_u	=	ultimate factored shear force, kip (kN)
W_u	=	ultimate factored load
Δ	=	maximum permissible deflection
ϵ_f	=	strain in GFRP flexural reinforcement
Φ	=	strength reduction factor
λ	=	size effect factor
ρ_f	=	reinforcement ratio

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