Design Comparison of One-way Slabs and Beams with Fiber-Reinforced Polymer (FRP) and Steel Reinforcing Bars

Overview

The purpose of this investigation is to compare the design of one-way slabs and beams using fiber-reinforced polymer (FRP) and steel reinforcing bars. The comparison is based on examples given in *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars*, ACI 440.1R-15. The following sections provide an overview of the investigation. A summary of the findings is given in the Conclusions section.

One-way Slabs

The comparison for one-way slabs is based on Example 4 in ACI 440.1R-15. The slab is 7 in. thick and is continuous over 3 or more 18-ft spans. Additional design data are as follows:

- Loads
  Dead load = weight of the slab
  Live load = 50 lb/ft^2
- Concrete
  Normalweight aggregate
  Specified compressive strength f_c' = 4,000 psi
- FRP reinforcing bars
  Guaranteed tensile strength f_{fu}^* = 95,000 psi
  Design modulus of elasticity E_f = 6,000 ksi
- Steel reinforcing bars
  ASTM A615 with f_y = 60,000 psi

The required FRP and steel reinforcement is given in Table 1; the FRP reinforcement is determined in Example 4.

Table 1 – Comparison of Required FRP and Steel Reinforcement for a One-way Slab

Reinforcement Type	Flexural Reinforcement		Shrinkage and Temperature Reinforcement
	Top	Bottom	
FRP	#6 @ 6 in.	#6 @ 6 in.	#4 @ 8 in.
Steel	#4 @ 10 in.	#4 @ 14 in.	#4 @ 14 in.

For the top flexural bars, the required area of FRP reinforcement is approximately 3.7 times greater than the required area of steel reinforcement. Because development lengths for FRP bars are longer than those for steel bars, the ratio of total volume of top FRP to steel bars is greater than 3.7. The area ratio of FRP to steel reinforcement is 5.1 for the bottom bars. The required FRP shrinkage and temperature reinforcement is approximately 1.8 times greater than the required steel shrinkage and temperature reinforcement.

The area of required FRP flexural reinforcement can be reduced by using a thicker slab, which is illustrated in Example 4. With a 12 in. slab thickness, the required FRP flexural reinforcement is #5 @ 7 in. at both the top and bottom of the slab. Thus, a 70 percent increase in slab thickness results in only a 40 percent reduction in FRP reinforcement.

Requirements for shear, crack control, deflections, and creep rupture must also be checked for the 7.0-in. slab with FRP reinforcement. Calculations for these requirements are not provided in Example 4; however, calculations using the provisions in ACI 440.1R-15 were performed in this investigation and it was determined that these requirements are satisfied. Shear and deflection requirements were also found to be satisfied for the one-way slab with steel reinforcement (crack control requirements were automatically satisfied based on the provided bar spacings and creep rupture is a requirement that is only applicable to members with FRP reinforcement).

Beams

The design comparison for beams is based on Example 3 in ACI 440.1R-15. The width of the beam is 12 in. and the depth is 20 in. The service dead and live load positive moments are given as 56 ft-kips and 35 ft-kips, respectively. Additional design data are as follows:

- Concrete
  Normalweight aggregate
  Specified compressive strength f_c' = 4,000 psi
- FRP reinforcing bars
  Guaranteed tensile strength f_{fu}^* = 80,000 psi
  Design modulus of elasticity E_f = 6,500 ksi
- Steel reinforcing bars
  ASTM A615 with f_y = 60,000 psi

The required FRP and steel reinforcement is given in Table 2. The FRP flexural reinforcement is determined in Example 3 and the FRP shear reinforcement was calculated in this investigation in accordance with Chapter 8 in ACI 440.1R-15.

Table 2 – Comparison of Required FRP and Steel Reinforcement for a Beam

Reinforcement Type	Flexural Reinforcement	Shear Reinforcement (each end of beam)
FRP	4-#8	4-#4 U stirrups @ 7 in., 10-#4 U stirrups @ 8 in.
Steel	4-#6	11-#3 U stirrups @ 8 in.

The required area of FRP flexural reinforcement is approximately 1.8 times greater than the required area of steel reinforcement. Because development lengths for FRP bars are longer than those for steel bars, the ratio of total volume of FRP to steel bars is greater than 1.8.

The required area of FRP shear reinforcement is approximately 2.3 times greater than the required area of steel shear reinforcement.

Conclusions

The following conclusions can be drawn from this investigation:

1. Significantly more reinforcement is required in one-way slabs with FRP reinforcement compared to those with steel reinforcement.

   One-way slabs with FRP reinforcement require approximately 4 to 5 times more flexural reinforcement and about 2 times more shrinkage and temperature reinforcement than one-ways slabs with steel reinforcement.

2. Significantly more reinforcement is required in beams with FRP reinforcement compared to those with steel reinforcement.

   Beams with FRP reinforcement require approximately 2 times more flexural reinforcement and 2 times more shear reinforcement than beams with steel reinforcement.

3. Because one-way slabs and beams with FRP reinforcement require larger amounts of reinforcement than those with steel reinforcement, the number of reinforcing bars placed in the field is likely to be larger as well. Thus, construction times are expected to be longer for members with FRP reinforcement.

4. A significantly greater number of design and detailing requirements need to be satisfied and a significantly greater number of calculations need to be performed for one-way slabs and beams with FRP reinforcement compared to members with steel reinforcement. Also, design methods and equations for members with FRP reinforcement are not as straightforward as those for steel reinforcement. This results in a substantial increase in design time for the structural engineer.