The application of polypropylene fiber for reinforced concrete beams and slabs

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Abstract. Currently there is no specific design standard for polypropylene (PP) fiber reinforced concrete structures. There are different conclusions on the bending strength of polypropylene fiber reinforced concrete structures. This paper presents some material properties of polypropylene fiber reinforced concrete. Based on the stress-strain state of the material, the stress diagram and the formula for calculation of the bending strength of the reinforced polypropylene fiber reinforced concrete with longitudinal bars structure were proposed. Bending strength of beams and slabs when using PP fiber were compared through examples and experiments.

1. Introduction
Although concrete offers many advantages regarding mechanical characteristics and economic aspects, the brittle behavior remains a significant limitation of the material. Specifically, for the seismic and other applications where flexible behavior is essentially required. Recently, the development of fiber reinforced concrete (FRC) has provided solutions to overcome the disadvantages of traditional concrete.

Fiber reinforced concrete standard ASTM C1116M-08 divides into 4 types of FRC: Type I is dispersed fiber reinforced concrete (SFRC) containing stainless steel, alloy steel, or carbon steel; Type II is fiberglass reinforced concrete (GFRC) containing durable alkaline glass fiber; Type III is synthetic fiber reinforced concrete (SynFRC); Type IV is natural fiber reinforced concrete (NFRC).

Polypropylene (PP) fibers were first proposed to be used as admixture for concrete in 1965 to construct buildings against explosive effects for the US Corps of Engineers. Nowadays, PP is often used as mono filament or fibrillated bundles (Figure 1 & Figure 2). Addition of fibers in concrete improves the toughness, flexural strength, tensile strength, tolerance, impact strength... while the price is low and the quality is stable.
PP fiber reinforced concrete shows great attention because of their ability to reduce the plastic shrinkage, crack expansion, environmentally sustainable, etc. While standards and guidelines for calculation of steel fiber reinforced concrete structure are available [4], [15], there are no specific design standards for PP fiber reinforced concrete. The study about cracking behavior and bearing capacity of beams is only studied on material and experimental levels [6], [8]. This report presents the scientific basis, proposed stress diagram and formula for determining bending resistance of dispersed PP reinforced concrete components with longitudinal bars. Bending resistance of beams and slabs using PP fiber concrete and traditional concrete were also compared through examples and experimental results.

2. Mechanical properties of concrete with discrete PP fiber

PP fiber content is often high in plate structures. In other applications, the fiber content is mainly used as admixture for crack control and it is often below 0.3%. It is rarely use for load bearing structures [3]. The mechanical properties of PP fiber concrete in term of compressive and tensile strength are following:

For compressive strength: PP fibers are not effective in increasing the compressive strength of concrete. The effect of low PP fiber content on the compressive strength of concrete is negligible, and when the fiber content is very high, it can cause turbulence, lumpiness and no effect to increase the compressive strength of concrete [3]. When using fibers with a volume content of 0.4%, the compressive strength of concrete only increased by 5% [6]. Some studies also indicate that when using a fiber weight of 0.5÷2 kg/m³ of concrete (or a volume content of less than 0.2%), the compressive strength increases, but is also negligible, only 10% to 20% [1], [2]. The increase of PP fiber content by 0.5%÷1% also reduces the compressive strength of concrete from 8% to 12% [3], [9]:

![Figure 3. Relation between compressive strength and % of fiber at different ages](image)
The effect of PP fiber in tensile strength of concrete is more noticeable. Using fibers with a volume content of 0.4%, the tensile strength of concrete is increased to 70% [6]. Results from a study [3] concluded that the tensile strength of PP fiber reinforced concrete increases by 20% to 50% compared to conventional concrete. This is due to the strength of the PP fiber concrete depends on fiber characteristics and construction methods. Tensile resistance of reinforced concrete is also maintained at the stage of cracked concrete [11] as shown in Figure 4.

Moreover, the addition of PP fiber has slightly affects on elastic modulus and compressive strength of the fiber concrete [3].

![Figure 4. Effect of Vf (0.4%; 0.6%; 0.8%) on average splitting tensile stress-displacement curve for PC and PPFRC with 25 mm fibres at 28 days.](image)

3. **Create formulas for calculating bending PP fiber reinforced concrete structures**

   Base on the stress diagram in the perpendicular section when calculating dispersed fiber reinforced concrete structures as shown in Figure 5 (given in Russian Standard SP 52-104-2006 [15]), adjust to suite the PP fiber reinforced concrete components.

![Figure 5. Stress diagram on the perpendicular section of steel fiber reinforced concrete bending component [15]](image)

   It has been proven that the tensile strength and strain capacity of PP fiber reinforced concretes were higher than that of plain concrete. That means, at the ultimate state, the concrete at tensile area should work together with the tensile longitudinal steel bars to resist the tensile stress. In order to make sure that condition happens, two problems need to be clarified: (i) the maximum tensile strain of PP fiber reinforced concrete, and (ii) the tensile strength value of fiber reinforced concrete at the limit state.
Determination the relationship tensile stress - strain in PP fiber reinforced concrete after the cracking of the matrix concrete is very difficult, requiring equipment to control the loading speed according to the deformation. According to a study of Karrar Ali Al-lami [6], the post concrete cracking phase of plain concrete differed from PP fiber reinforced concrete samples as shown in Figure 6. While it is not possible to determine the maximum strain due to the limitations of the strain gage capacity, but it proved that PP fiber reinforced concrete could continue bear tensile. Due to the dispersion PP fibers were bridge linked together, the tensile sample is failure when the PP fibers are broken or slipped from the matrix concrete.

Figure 6. Tensile stress vs strain of concrete and PP fiber concrete from test [6]

In the experimental results of M. Tavakoli [13], the effect of different percentage by volume of PP fiber on the ultimate tensile strain of PP fiber reinforced concrete was clarified in Figure 7:

Figure 7. Tensile strain versus volume percent of PP fiber [13]

Based on the reason above, with low fiber content of 0.2%, 0.3%, the ultimate tensile strain of PP fiber reinforced concrete is 0.3%. This strain ensures that PP fiber concrete and tensile longitudinal steel bars can work together at the ultimate stage. From the above experimental results, it is also possible to take the tensile stress value of PP fiber reinforced concrete at the strength limit state of the bending components is 50% of the tensile strength of PP fiber reinforced concrete as Fig. 6.

Stress diagram on the perpendicular section of discrete PP fiber concrete bending component with longitudinal steel bars is shown in Fig. 8:
The formula determines the strength on the perpendicular section of discrete PP fiber concrete bending component with longitudinal steel bars as follows:

\[
M_{ull} = R_{fb} \theta (h-0.5x-a) + R_{st} A_x' (h-a-a') - \sigma_{ft, crc} b (h-x) \left( \frac{h-x}{2} - a \right)
\]

The height \( (x) \) of compressive area concrete is determined from the condition:

\[
R_{st} A_x' + R_{fb} b x = \sigma_{ft, crc} b (h-x) + R_x A_x
\]

in which, \( A_x; A_x' \) : cross sectional area of tensile, compressive longitudinal steel bars

\( R_{fb} \) : compressive strength of PP fiber concrete

\( \sigma_{ft, crc} \) : tensile stress value of PP fiber reinforced concrete at the strength limit state, equal to 50% of the tensile strength of PP fiber concrete \( (R_{ft}) \).

4. Experimental results

Experimental data for two testing beams with identical configurations but different type of concrete (reinforced concrete and PP fiber reinforced concrete). The experimental setup can be seen in Fig. 5: \( b \times h = 33 \times 20 \) cm; \( A_x = 2\phi 12 \) - CII; \( A_x = 3\phi 25 \) - CB400-V; plain concrete B35; \( R_{fb} = 20.8 \) MPa; \( R_{ft} = 1.65 \) MPa.

Figure 9. Experimental setup for testing PP fiber reinforced concrete beam in Lab of Hanoi Architectural University
Results according to the proposed formulas, the difference in bending resistance are 5.17% when using two types of concrete:
- Using plain concrete: \( M_{\text{ut}} = 68.712 \) (kNm)
- Using PP fiber concrete: \( M_{\text{ut}} = 72.267 \) (kNm).

Experimental results, the difference in bending resistance are 3.03%:
- Using plain concrete: \( M_{\text{ut}} = 82.288 \) (kNm)
- Using PP fiber concrete: \( M_{\text{ut}} = 84.784 \) (kNm).

Such differences show that the proposed formula is reliable.

5. Experimental results
Bending strength of beams and slabs when using PP fiber were compared through examples and experiments as the following.

5.1. Example 1
Calculation the bearing capacity of the beam with rectangular cross section is 20*40cm and tensile longitudinal steel bars are 3\( \Phi \)20 - CB300-V, in two cases: (i) using plain concrete B15; and (ii) PP fiber concrete with a fiber content of 0.8 kg/m³. Calculated data on table of TCVN 5574:2018 standard and experimental data [1]: \( R_b = 8.5 \) MPa; \( R_{fb} = 9.02 \) MPa; \( R_{fbt} = 1.21 \) MPa; \( R_s = 280 \) MPa.

Applying the formula in Section 3, calculating the bearing capacity of the beam:
(i) For plain concrete: \( M_{\text{ut}} = 75.809 \) (kNm).
(ii) For PP fiber concrete: \( M_{\text{ut}} = 80.354 \) (kNm) \( \rightarrow \) 6% increase compared to case (i).

5.2. Example 2
Calculation the bearing capacity of the slab with a thickness of 10 cm and reinforcement steel \( \Phi \)6 a150 - CB240, in two cases: (i) using plain concrete B15; and (ii) PP fiber concrete with a fiber content of 0.8 kg/m³.

Calculated data on table of TCVN 5574:2018 standard and experimental data [1]: \( R_b = 8.5 \) MPa; \( R_{fb} = 9.02 \) MPa; \( R_{fbt} = 1.21 \) MPa; \( R_s = 225 \) MPa. Choose protective concrete layer is 1 cm.

Applying the formula in Section 3, calculating the bearing capacity of the slab:
(i) For plain concrete: \( M_{\text{ut}} = 3.591 \) (kNm);
(ii) For PP fiber concrete: \( M_{\text{ut}} = 6.011 \) (kNm) \( \rightarrow \) 67% increase compared to case (i).

5.3. Discussion
Two examples show that the bending resistance of a slab using PP concrete is significantly higher than that of a plain concrete slab, this effect in the beam structure is negligible. The content of tensile longitudinal steel bars in slabs is low, the role of the tensile PP fiber reinforced concrete area is increases, so effect of them on the bending resistance of the slabs much higher than that of beams.

6. Conclusion
In this study, the formulas for calculating strength of PP fiber reinforced concrete structure with longitudinal steel bars were proposed. Those formulas were accounted for the bearing capacity of the tensile zone concrete. The results from experimental testing showed the similar results calculated from proposed formulas. In addition, the application of PP fibers in concrete was not only effective in limiting crack expansion, increasing the flexibility for structures, but also improve a considerable bearing capacity for slabs (low content of tensile longitudinal steel bars).

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