Proceedings of the 2nd International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/91/20241073

The ways and mechanisms of using CFRP materials to strengthen the flexural performance of reinforced concrete beams

Junyi Zhang

Department of engineering and technology, China University of Geosciences Beijing, Beijing, China

13012719621@163.com

Abstract. Due to the increasing demand for structural strengthening and retrofitting solutions, Fiber-reinforced plastic (FRP) materials has emerged as a promising technology to improve the performance of existing structures. FRP material is a composite material composed of fiber-reinforced plastics, known for its excellent strength and resistance to corrosion. The primary components of this material consists of various fibers, such as glass fiber, carbon fiber, or aramid fiber, along with a resin matrix, such as epoxy resin, polyester resin. FRP materials are commonly employed in construction engineering to enhance the flexural strength of concrete structures. This paper, through methods of literature review and building physical models, investigates the effectiveness of Carbon Fiber Reinforced Polymer (CFRP) materials in enhancing the bending strength of reinforced concrete beams. This study aims to examine the impact of carbon fiber reinforced polymer (CFRP) sheets on the flexural strength of reinforced concrete beams, which aims to establish calculation formulas based on the specific impacts observed. The findings of this study demonstrate the capacity of FRP materials, specifically CFRP materials, to improve the bending strength of reinforced concrete beams. The usage of FRP materials for structural reinforcement offers a durable, corrosion-resistant, and lightweight solution that can prolong the lifespan and improve the structural efficacy of existing infrastructure.

Keywords: CFRP materials, reinforced concrete beams, flexural strength.

1. Introduction

Reinforced concrete structures are widely used in the construction due to their exceptional strength and durability. However, the deterioration of infrastructure due to the passage of time and the increased demands placed on it have necessitated the implementation of effective strengthening techniques to enhance the performance and safety of existing structures. Fiber Reinforced Polymer (FRP) materials are a promising solution for strengthening reinforced concrete elements, offering advantages such as a high strength-to-weight ratio, corrosion resistance, and ease of application.

Carbon Fiber Reinforced Polymer (CFRP) material is a composite material that consists of carbon fiber or carbon fiber fabric as the reinforcing body, and resin, ceramics, metals, cement, carbon as the matrix. This article expresses the capacity of CFRP materials to enhance their bending resistance by conducting a literature review and developing component physical models.

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Significant progresses have been made in the research on the flexural performance of reinforced concrete beams strengthened with CFRP materials. Oral Buyukozturk conducted many experiments to explain the phenomenon of brittle debonding failure in FRP material. By using a model-based approach, his study determined the impact of debonding on the performance and durability of FRP reinforcement [1]. Scholar Junwei Zhang conducted the flexural tests on five reinforced concrete beams that were strengthened with carbon fiber reinforced polymer (CFRP) sheets, which aimed to investigate the influences of span-depth ratio on flexural performance [2]. Wenxue Dong proposed the application of FRP materials in bridge engineering and identified the challenges associated with FRP composite materials. He also anticipated the main areas of development in this field [3]. Zekun Yang presented a mathematical technique to calculate the flexural bearing capacity of reinforced concrete short beams reinforced with externally bonded FRP sheets. Moreover, the calculation process incorporated the compressive stress-strain curve of Hognestad concrete, which includes a falling portion [4].

This paper aims to propose a technique for strengthening the bending capacity of CFRP materials and a straightforward formula for calculating the bending bearing capacity. These findings have practical significance for using CFRP to strengthen reinforced concrete beams.

2. CFRP materials' characteristics

Carbon Fiber Reinforced Polymer(CFRP) materials offer several advantages for strengthening beams and enhance their bending strength. Here are some key characteristics of CFRP materials.

2.1. High Strength-to-Weight Ratio

CFRP materials can provide significant strengthening effects without adding excessive weight to the structure, making them ideal for implementations where weight is a concern. CFRP materials use high-strength carbon fibers as reinforcing materials, which have much higher strength than traditional ones. CFRP materials use lightweight polymers as the matrix, usually with resins such as epoxy resin and polyimide, which have good adhesion and chemical corrosion resistance while also helping to reduce the weight of CFRP materials. The above conditions have created the high strength-to-weight ratio characteristics of CFRP materials.

2.2. Corrosion Resistance

Unlike traditional steel reinforcements, CFRP materials are highly resistant to corrosion. The basic components of CFRP like carbon fiber and polymer matrix are non-metallic and resistant to electrochemical reactions. Commonly used polymer matrices, such as epoxy resin and polyimide, have good chemical corrosion resistance and can effectively resist the erosion of acidic, alkaline, saline, and other media. CFRP material is a composite structure composed of multiple layers with high density and uniform structural characteristics, which can effectively block the penetration of corrosive media delay the aging and corrosion rate of the material. Ziye Pan further studied the aging control and corrosion resistance of FRP materials [5].

2.3. Elastic Change Ability

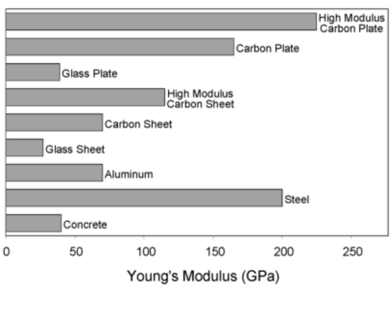

Figure 1. Elastic (Young 's) modulus [1]

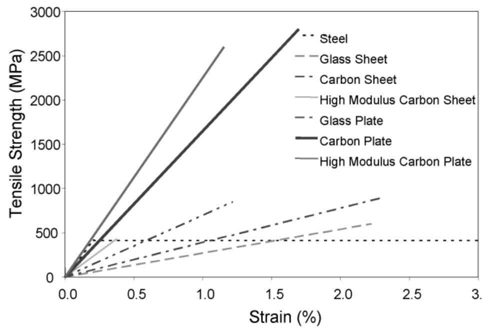

Figure 2. Stress-strain behavior [1]

From the two figures, it is clear that the Elastic modulus of CFRP material compositions are considerably less than that of steel. Figure 1 compares the elastic modulus of concrete, aluminum, and steel with those of several commercially available FRP composite systems, and Figure 2 shows a comparison of strength-strain behavior in tension [1]. Although the Young's modulus of FRP materials may be lower than that of metal materials, their high specific strength, corrosion resistance, design flexibility, and other advantages make them a high-quality material chosen to enhance bending performance. Especially in applications that require lightweight design, long-term durability, and excellent chemical performance, FRP can significantly improve the performance and service life of structural components.

3. The flexural performance of reinforced concrete beams

Reinforced concrete has many applications in engineering, among which beam components are the main ones. Beam components mainly bear bending moments and are typical bending resistant components. Therefore, reasonable design should be carried out in the design to prevent beams from bending failure or even brittle failure, causing economic losses and health and safety risks. Therefore, understanding the bending failure mode of beams is very helpful for structural design and later reinforcement.

For reinforced concrete beams, different reinforcement ratios, cross-sectional areas, and levels of concrete strength will have a significant impact on the flexural bearing capacity of the beam, with reinforcement playing a particularly important role. Taking a simply supported beam as an example, this issue can be addressed.

3.1. Under- and over-reinforced failure

In under-reinforced circumstances, the reinforcement ratio of the beam is too low. Before the concrete compression zone fails, the steel bars reach the yield stage in a short period of time, and the beam fails in a short period of time. This type of failure is similar to the brittle failure form of plain concrete.

In the over-reinforced term, the reinforcement ratio of the beam is too high, and the concrete in the compression zone of the reinforced concrete beam is damaged in a short period of time. This underutilization of the steel bars' tensile strength in the tension zone leads to brittle failure and is economically unreasonable.

3.2. Balanced failure

The reinforcement ratio is between under-reinforced failure and over-reinforced failure. The yield of the steel bars in the tensile zone initiates the failure of the beam, followed by the crushing of the concrete in the compressive zone. This failure fully utilizes the strength of the steel bars and concrete, and plastic deformation and crack development are obvious, which is ductile failure.

Over-reinforced and under-reinforced failures should be avoided in structural design, as they can cause rapid damage. Balanced failure is a normal form of failure, and its failure has good ductility [6]. So it can be a useful way to use FRP materials to enhance their bending resistance and ductility.

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4. Strengthening method and mechanism

The flexural bearing capacity of reinforced concrete beams is mainly provided by the lower-tensile steel bars. When it undergoes bending failure, the lower concrete cracks and the tensile steel bars yield, these two characteristics provide a good idea to enhance the flexural capacity. CFRP cloth can be posted at the bottom of the concrete tensile zone to help the tensile steel bars bear the bending moment, delay and reduce concrete cracking, and enhance the ductility of reinforced concrete beams [7].

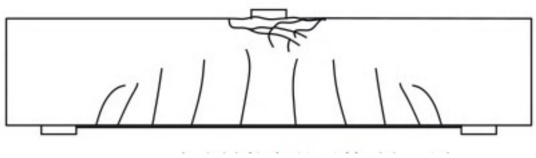

Figure 3. Installation method

From the Figure 3 it can be seen that the method to enhance the bending capacity of a beam is like adding steel bars to the compression zone of the beam. Therefore, the similar method can be used to derive the calculation formula for the bending bearing capacity of the beam cross-section.

4.1. Computational model

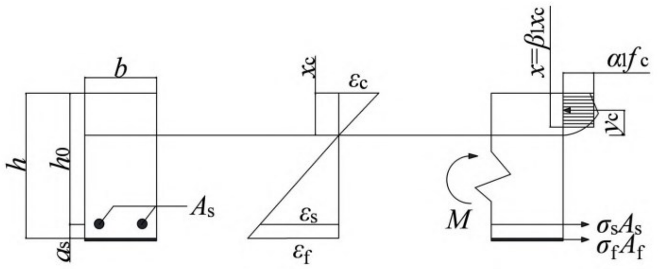

Figure 4. Model after posting CFRP cloth [4]

Figure 4 is the computational model of the beam after posting CFRP cloth, referring to Code for Design of Concrete Structures GB 50010-2010. To simplify the calculation, the stress graph of the concrete in the compression zone is replaced with an equivalent rectangular stress graph, and the rectangular stress graph coefficients α_1 and β_1 for the concrete in the compression zone. The following formula can be therefore obtained:

$$\alpha_1 f_c bx = k_1 f_c bx_c \quad (1)$$

$$x = 2(x_c - yc_c) = 2(1 - k2)x_C \quad (2)$$

$$\beta 1 = \frac{x}{xc} = 2(1 - k2) \quad (3)$$

$$\alpha_1 = \frac{k_1}{\beta_1} = \frac{k_1}{2(1 - k_2)} \quad (4)$$

where α_1 is the ratio of the stress value of the concrete rectangular stress in the compression zone to the design value of the concrete axial compressive strength. And β_1 is the ratio of the height of the compressed area in a rectangular stress diagram to the neutral axis.

4.2. Calculation formula

By converting Formula (1) and Formula (2), as well as knowing the design value of the tensile strength of CFRP material (σf), the calculation formula can be obtained for the flexural bearing capacity of reinforced concrete beams with CFRP cloth posted on them, as follows:

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$$\alpha_1 f_c bx = \sigma_s A_s + \sigma_f A_f \quad (5)$$

$$M_u = \sigma_s A_s \alpha_d \left(h_0 - \frac{x}{2}\right) + \sigma_f A_f \alpha_d \left(h - \frac{x}{2}\right) \quad (6)$$

As the span-to-height ratio of the beam decreases, the strain distribution of the mid-span normal section becomes increasingly inconsistent with the plane section assumption, and the internal force arm gradually decreases. Therefore, it is necessary to introduce an internal force arm correction coefficient to modify the shallow beam formula that conforms to the assumption of a flat section. Referring to the Code for Design of Concrete Structures GB 50010-2010, it can be obtained that:

$$\alpha_d = 0.8 + 0.04 \frac{l_0}{h} \quad (7)$$

where l0 means short beam calculation span [4]. This process is similar to the calculation of the flexural bearing capacity of the normal section of a reinforced beam, and it also shares a similar failure mode, with problems of over-reinforcement and under-reinforcement failure. So, when strengthening the bending resistance of beams, these issues should also be considered.

4.3. Calculation instance

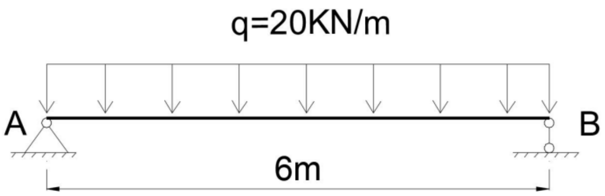

Figure 5. Force diagram

The cross-sectional dimensions of this reinforced concrete beam are b*h=250*500, the strength grade of concrete is C30, the environmental category is Class 1, and the steel bars are made of HRB400 grade steel bars. From the Design of Concrete Structures GB 50010-2010, it can be seen that σ_s =360N/mm^2, f_c =14.3N/mm^2, f_t =1.43N/mm^2, α_1=1.0, and As=1256mm^2.

When the load shown in the figure is applied, the tensile steel bars originally configured in the structure are not sufficient to provide enough bending capacity, so the CFRP cloth is posted to enhance its bending capacity. The following formula can be used:

$$M_u = \alpha 1 f_c bx \left(h_0 - \frac{x}{2}\right) \quad (8)$$

Through force analysis, it can be calculated that M=Mu=360KN*m, x=228mm, and the initial configuration of tensile steel bars is not sufficient to provide sufficient bending bearing capacity:

$$M_u > \sigma_s A_s \alpha_d \left(h_0 - \frac{x}{2}\right) \quad (9)$$

So it is necessary to post CFRP sheet to improve its bending resistance. The following formula can be used to determine at least how much bending bearing capacity CFRP fabric is required, and then determine the specifications and parameters of the CFRP fabric to be posted.

$$M_u - \sigma_s A_s \alpha_d \left(h_0 - \frac{x}{2}\right) = \sigma_f A_f \alpha_d \left(h - \frac{x}{2}\right) \quad (10)$$

5. Conclusions

This paper examines the failure modes of reinforced concrete beams and the performance characteristics of CFRP materials. It concludes that using CFRP reinforcement effectively improves the bending

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strength and failure extension of the beam, and analyzes the mechanism behind reinforcing the bending capacity of beams with CFRP reinforcement and derives a calculation formula to access the bending performance of beams. This has a reference value for the technique of reinforcing flexural components and the process of cost calculation. However, there are still certain shortcomings. Following the installation of CFRP bars, their failure mode has also changed, resulting in the emergence of failure-related issues. The method of posting FRP bars is still worth discussing, including the impact of temperature and other conditions on the installation processes. FRP materials have low elastic change ability, hence achieving improved results can be accomplished by applying pre-tension to the FRP reinforcement, effectively converting it into prestressed reinforcement.

The widespread implementation of CFRP materials will lead to a movement towards making structures lighter, which in turn helps to reduce energy consumption and carbon emissions, therefore promoting the sustainable development of the environment. Furthermore, a more profound comprehension of the properties of CFRP materials can equip engineers and designers with a wider range of innovative design choices, optimizing product performance and minimizing expenses.

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