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Structural Performance of Reinforced Concrete Beams Strengthened with CFRP Plats under Static and Repeated Loads

A Thesis Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for Master Degree of Science in Civil Engineering– Structural Engineering.

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ABSTRACT

Structural Performance of Reinforced Concrete Beams Strengthened with CFRP Plats under Static and Repeated Loads

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External strengthening using CFRP plates is an effective technique to enhance the flexural or shear capacity of reinforced concrete members due to their high strength, low weight, and excellent corrosion resistance. This study presents an experimental and numerical investigation on eight simply supported reinforced concrete beams (225 × 325 × 1600 mm) with a compressive strength of 33 MPa. The beams were divided into two groups: the first was designated for flexural strengthening using two side-by-side CFRP plates in the tension zone, while the second was for shear strengthening with shorter strips bonded to the beam sides. Reference beams were also included for comparison, and all specimens were tested under both static and repeated loading.

The experimental results showed that flexural strengthening improved the cracking load by 16.25% and the ultimate load by 13.39% under static loading, while under repeated loading the improvements were 55% and 11.43%, respectively. For shear strengthening, the cracking load improved by 23.8% and 26.7%, and the ultimate load increased by 19.7% and 20.6% under static and repeated loading, respectively.

In the numerical analysis, ABAQUS was employed using the Concrete Damaged Plasticity (CDP) model to represent concrete and an orthotropic model to represent the CFRP plates, assuming perfect bond. The numerical results showed close agreement with the experiments, with a difference of 1.37% in ultimate load and 8.66% in mid-span deflection. Moreover, the

additional models combining flexural and shear strengthening demonstrated further performance gains of 34.2% under static loading and 28.2% under repeated loading compared to the reference beam.

The MAPEI Structural Design software, based on ACI 440.2R-17, was also used to estimate the required CFRP reinforcement. The program inputs included beam geometry, reinforcement details, concrete properties, and applied loading. The theoretical predictions showed acceptable agreement with the experimental results, confirming the validity of the software as a fast and reliable code-based tool for CFRP design.

HAPTER ONE

INTRODUCTION

1.1 Introduction

Reinforced concrete (RC) beams are essential structural elements designed to resist bending and shear forces through the composite action of steel reinforcement and concrete. However, their performance may deteriorate over time due to strength degradation, cracking, and stiffness loss under sustained service conditions (Darwin et al., 2016). To address such deterioration, conventional strengthening methods, such as section enlargement and steel jacketing, have been adopted. While effective, these techniques are often associated with increased structural weight and susceptibility to corrosion (ACI Committee 440, 2017).

In recent years, fiber-reinforced polymers (FRPs), particularly carbon fiber-reinforced polymer (CFRP), have gained prominence as a superior alternative owing to their high strength-to-weight ratio, corrosion resistance, and ease of installation. CFRP is now widely employed to enhance the flexural and shear performance of RC beams under both static and repeated loading conditions (Boutlikht et al., 2022; Kaliyappan & Pakkirisamy, 2023; Yousif, 2012).

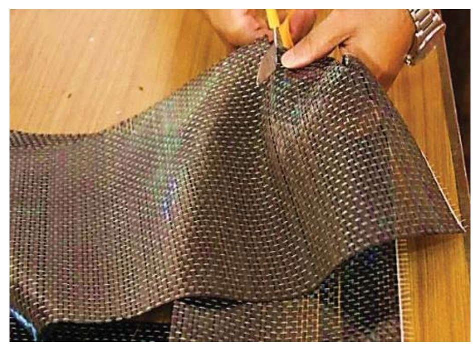
1.2 Carbon Fiber Reinforced Polymer (ACI Committee 440, 2017)

Carbon Fiber Reinforced Polymer (CFRP) is a composite material consisting of high-strength carbon fibers embedded within a polymer matrix. It is widely employed in structural strengthening applications, primarily through two main techniques: the Externally Bonded Reinforcement (EBR) method, in which laminates or sheets are bonded to the surface of the structural element; and the Near-Surface Mounted (NSM) method, which involves embedding CFRP rods into pre-cut grooves that are subsequently filled with epoxy resin. CFRP is available in various forms including:

- Laminates/Plates: Thin, stiff strips externally bonded to improve flexural or shear capacity.
- Sheets/Fabrics: Flexible carbon fiber applied with epoxy, used in multiple orientations (e.g., U-wraps) for flexural and shear strengthening.
- NSM Bars/Rods: Inserted into shallow grooves and bonded with epoxy, commonly used for shear and flexural enhancement.
- Wrapping/Jacketing: Continuous fiber wraps used around beams or columns to improve confinement and shear resistance and prevent brittle failure.

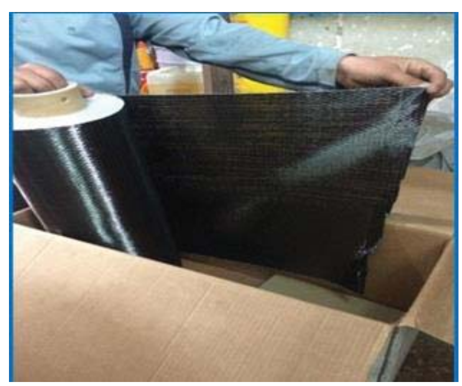
The Figure (1-1) below illustrates the different types of CFRP.

a. CFRP-Plate (Abed et al., 2022)



b. CFRP- Sheet (Prashob et al., 2017)

c. CFRP-Bars (Tstar Co., n.d.)



d. CFRP-Wrap (Hassan.,2016)

Figure (1-1): Types of CFRP

1.2.1 Carboplate E 170

Carboplate E170 is a high-performance carbon fiber reinforced polymer (CFRP) plate developed by MAPEI through the pultrusion process. In this automated manufacturing method, continuous strands of high-strength carbon fibers are drawn through an epoxy resin bath for complete impregnation, then shaped and cured in a heated mold to achieve consistent geometry and performance. To preserve surface quality and eliminate the need for pre-installation cleaning, a protective plastic film (peel-ply) is applied to both sides of the plate, as illustrated in Figure (1-2).

Specifically designed for the external strengthening of concrete, timber, masonry, and steel structures, Carboplate E170 offers a wide range of applications. These include flexural strengthening of reinforced concrete beams and slabs, rehabilitation of structural elements damaged by fire or earthquakes, enhancement of resistance to dynamic loads and vibrations, upgrading of aging roofs and floors, and reinforcement of bridges and ramps subjected to increased service loads (MAPEI Corporation, 2023).

Figure (1-2): Carboplate E170 (MAPEI Corporation.,2023).

1.2.1.1 Carboplate's Technical Characteristics [MAPEI Corporation, 2023]

1. Exceptional tensile strength, reaching up to 3100 MPa
2. High modulus of elasticity, depending on the type, with values up to 250 GPa (e.g., E170–E250).

3. Excellent strength-to-weight ratio combined with lightweight properties, making it ideal for structural applications.
4. Superior resistance to dynamic vibrations and fatigue, ensuring long-term performance under cyclic loading.
5. Highly resistant to extreme climatic conditions and alkaline environments, with non-corrosive properties that ensure durability in harsh settings.
6. Ease of installation, requiring no heavy tools or specialized equipment.
7. Easily cut to the required length on-site, providing flexibility during installation.

1.3 Problem Statement

Reinforced concrete beams, when subjected to static or repeated loading, often experience premature failure due to flexural cracks, shear deficiencies, or debonding issues. Although several strengthening methods using externally bonded CFRP have been investigated, the effectiveness of Carboplate laminates in enhancing both flexural and shear performance under repeated loading remains insufficiently understood. Moreover, limited studies have combined experimental testing, numerical modeling, and design verification using specialized software to provide a comprehensive assessment. This gap highlights the need for a systematic investigation into the structural performance of RC beams strengthened with Carboplate under different loading scenarios.

1.4 Objectives

The specific objectives of this research are as follows:

- To evaluate the improvement in flexural and shear performance of simply supported RC beams strengthened with externally bonded CFRP plate under static and repeated loading conditions, with the aim of assessing their structural capacity and failure behavior.

- To develop and validate a reliable finite element model for reinforced concrete beams, and to employ this model in assessing the structural performance and failure mechanisms of beams strengthened with CFRP plate in flexural and shear zones under static and repeated loading.
- To employ the MAPEI Structural Design software as an alternative computational tool to manual calculations for flexural strengthening, with the aim of verifying accuracy, improving efficiency, and ensuring compliance with ACI 440.2R provisions.

1.5 Layout Thesis

The six chapters that make up this thesis each focus on a different facet of the investigation:

- **Chapter One:** Chapter One provides an overview of RC beam strengthening with FRP—particularly CFRP—introduces Carboplate E170 and outlines the research problem, objectives.
- **Chapter Two:** This chapter reviews key experimental and numerical studies on RC beam strengthening with FRP, emphasizing CFRP applications and concludes by outlining the study's contributions.
- **Chapter Three:** An experimental program was carried out to investigate the performance of simply supported RC beams strengthened with CFRP plate under static and repeated loading. It included material properties, specimen design, casting, testing procedures, and measurement techniques.
- **Chapter Four:** This chapter presents and discusses the experimental findings, including applied loads, deflections, concrete and reinforcement strains, and load–deflection behavior.
- Chapter Five: This chapter presents the numerical analysis of RC beams strengthened with CFRP plate using ABAQUS modeling and MAPEI Structural Design Software based on ACI 440.2R provisions.

- **Chapter Six:** This chapter outlines the conclusions drawn from the study and provides recommendations for Practical in field and future research.