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Behavior of a concrete bridge cantilevered slab reinforced using NSM CFRP strips

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HIGHLIGHTS

▶ Strains in CFRP NSM reinforcement and concrete were measured in a bridge concrete slab in a 2-year period.
▶ Service loads developed 8% of the concrete slab ultimate strength.
▶ CFRP NSM reinforcement greatly improved ultimate and yield loads of the reinforced elements.
▶ Model proposed by ACI4402R underestimated ultimate load of reinforced beams by 30%.

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ABSTRACT

Concrete beam strengthening using near surface mounting (NSM) carbon fiber reinforced polymers (CFRP) have shown excellent performance. However, the behavior of these elements in real structures has not yet been deeply studied.

This paper presents results, taken over a 2-year period, of a field investigation of the behavior of NSM CFRP reinforcement in a concrete bridge under service conditions. Also, four RC beams were tested in the laboratory under monotonic load to study behavior under ultimate conditions.

In service conditions, strains in concrete and CFRP were 42% and 6% of the ultimate capacity, and the concrete slab developed 8% of its ultimate strength, confirming that CFRP improved bridge performance.

The results from laboratory tests of CFRP reinforced beams, and the measurements of concrete and CFRP deformations taken at the concrete bridge suggest that the NSM CFRP reinforcement used is effective, and that the strength of the reinforced bridge is adequate.

1. Introduction

Over the past decade, concepts of retrofitting and reinforcement of existing structures have gained great importance because existing highway infrastructure is ageing and deteriorating all over the world. There are many deterioration causes such as: environmental degradation, lack of maintenance, increase of traffic flow on major highways, and mistakes during design or construction phases. Under these scenarios, the alternatives of repairing and retrofitting structures are quite attractive because reconstruction involves higher costs and major demands of time and available space, not to mention the possible impact on users.

To repair and retrofit structures in this scenario, new techniques shall be properly developed and understood. Fiber reinforced polymers (FRPs) offer advantages over conventional construction materials as it is a non-corrosive material, it has high stiffness-to-weight ratio and strength-to-weight ratio, it possesses non-magnetic properties, and it is easy to transport and handle [1,2]. Other advantages of FRPs include: low thermal expansion coefficient, good fatigue performance damage tolerance, and low energy consumption during fabrication [2]. Also FRPs have unlimited size, geometry and dimension availability [3].

One method of FRP strengthening that has been widely used is externally bonded carbon fiber reinforced polymer (EBR CFRP), with laminates being the most common method. In EBR applications, the surface of the concrete is cleaned and prepared, and epoxy is applied in order to bond CFRP sheets to the concrete. This technique has been investigated by many researchers; e.g., [4–9]. Among those, some have focused on the failure mode of EBR on concrete beams, and they concluded that under monotonic load, the main failure mechanism would be debonding at adhesive-concrete interface [5,6]. The maximum strain recorded in both investigations was one third of the FRP ultimate value; which indicates that the FRP used in the EBR technique did not reach full capacity. In addition, Arduini and Nanni [6] found that the effectiveness of EBR strongly depends on concrete surface preparation,

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as they observed reductions of 19% in ultimate loads when poor surface cleaning was done before EBR installation.

In the near surface mounting (NSM) technique, CFRP is bonded into grooves in the concrete surface filled with epoxy. NSM CFRP has shown great advantages in terms of durability and flexural strengthening with respect to EBR technique because the surrounding concrete protects FRP so that mechanical and thermal damages become unlikely. Other advantages include improved bonding and bond transfer with the surrounding concrete and the ability to increase flexural capacity when they are under compression (negative moment) [10]. Also, NSM does not require extensive surface preparation as compared to EBR technique [11].

Even though NSM CFRP reinforcement appears as a promising technique, existing knowledge is still limited and even less so than EBR FRP method; in fact, only recently ACI440 [12] has included design guidelines for the NSM technique.

Concrete beams reinforced using NSM CFRP and tested under monotonic load exhibited superior flexural behavior (yield load and ultimate load) compared to beams without CFRP [1,3,10,13,14]. Barros [1,3] tested reinforced beams by using CFRP NSM strips and observed that reinforced beams increased their ultimate loads between 22% and 39% and their yield loads between 78% and 91% with respect to beams without CFRP. Al-Mahmoud [14] observed an increased in the ultimate load using NSM CFRP reinforcement by at least 50% and an increase in the cracking load between 5.7% and 75%.

Klowak [15] evaluated concrete slabs, under monotonic load, reinforced with different materials: steel, embedded glass FRP (GFRP), and CFRP. Those results showed similar ultimate loads for the specimens reinforced with the three types of reinforcements. GFRP showed an ultimate load 2% and 5% lower than that of steel and CFRP, respectively. Also steel reinforced specimens showed 12.7% and 38.6% lower deflections than GFRP and CFRP reinforced specimens, respectively.

Studies carried out on ductility of structures reinforced using CFRP materials have obtained varied results. For instance, Yost [10] observed reductions in ductility for specimens reinforced with NSM CFRP between 6.6% and 22% compared to control beams while Badawi [16] obtained reductions up to 30%. On the other hand, Aidoo [4] observed an increase in ductility of 9.7% for NSM CFRP specimens compared to control specimens. Hence, there is no agreement on whether NSM CFRP increases or decreases ductility.

Regarding CFRP strain effectiveness, Barros [3] measured ultimate strains of CFRP strips in concrete beams reinforced with NSM CFRP technique and tested for flexural strength. Measured strains ranged from 62% to 91% of the CFRP ultimate strain, proving that this strengthening technique has a high effectiveness level.

Different failure modes have been reported for NSM CFRP reinforced concrete beams under monotonic load: concrete crushing after yielding of steel reinforcement followed by failure of the CFRP reinforcement [4,13], and concrete crushing without failure in the CFRP [11].

Over the last decade the use of CFRP strips in existing structures using NSM technique has increased significantly; some examples are Martin Springs Bridge in Missouri, USA, and Maple Leaf Meats fabric slab in Montreal, Canada. However, there are no quantitative data available for these applications. To the authors' best knowledge, the only study on field performance of CFRP reinforced structures was carried out by Abdessemed [17]. This study evaluated a CFRP concrete bridge by means of dynamic analysis by ambient excitation; however, repair techniques involved in the study were concrete jacketing of piles, flexural, and shear strengthening for the beams using EBR CFRP sheets and laminates.

Summarizing, behavior of reinforced concrete beams using the promising technique of NSM CFRP strips has been studied by a few researchers over the last decade. Available laboratory studies have focused on monotonic and fatigue loads and have shown an improvement of beams structural capacity. However, field performance of concrete structures reinforced by this technique requires further investigations.

2. Research significance

The purpose of this research is structural evaluation of the NSM CFRP technique used in an actual concrete structure. Such evaluation considers measuring performance under actual service conditions; variable vehicular loads, ambient temperature and humidity conditions. Such field study is complemented by a laboratory study that represents some aspects of the field concrete members and it is focused on ultimate capacity of reinforced specimens.

3. Research program and strengthening technique

The current research proposes a dual-approach to assess the performance of NSM CFRP reinforcement by a field- laboratory experimental program.

The field portion aimed to assess the behavior of CFRP reinforcement used in Centenario Bridge in Santiago, Chile, in order to evaluate the influence of cyclic loads and superimposed loads in a 2-year monitoring period, under real conditions. This portion focused on the NSM CFRP reinforced cantilevered concrete slab of the bridge.

The laboratory study aimed to assess the behavior of CFRP reinforcement under ultimate condition. Small reinforced concrete beams, reinforced with NSM CFRP, were tested under monotonic loads and compared to reinforced concrete control specimens. Concrete beams were designed and reinforced to emulate some aspects of the cantilevered concrete slab existing in Centenario Bridge.

Centenario Bridge was built in 1987 having three spans of 61.1 m, 80.0 m, and 64.1 m each. The bridge structure comprises two post-tensioned concrete box girders with a common 27-m wide concrete top flange with flexible pavement structure built atop. The cross section of the box girders varied according to the flexural moment [18]. Some steel reinforcement (active and passive) is shown in Fig. 1. Active reinforcement was comprised of 16 ducts; each duct was filled with 12 0.6 in.-diameter (15 mm) dywidag tendons of 1862 MPa ultimate strength; each tendon was initially prestressed with 1452 MPa.

Due to the traffic increase over the last two decades, the Ministry of Public Works decided to increase Centenario Bridge from six to eight lanes by eliminating sidewalks and building a separate pedestrian bridge nearby.

The new traffic lanes were placed over the cantilevered slab (upper flange of the box girders) and the existing metallic barrier was replaced by a New Jersey barrier. As a consequence, the design strength in the reinforced concrete cantilevered slab was exceeded at some locations. Because of its low self-weight and relatively small dimensions (2×16 mm), CFRP strips were considered as a method to reinforce the cantilevered slab (see Fig. 1). The NSM technique was the attractive option for flexural strengthening in the slab's negative moment because EBR would be subjected to mechanical and environmental damage and would require a protective cover [19].

3.1. Experimental program

The field study focused on the bridge service performance (dead and live loads), and measured strains in the CFRP reinforcement and in the concrete surrounding the CFRP strips on the cantilevered slab.