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Axial load-bending moment diagrams of GFRP reinforced columns and GFRP encased square columns

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HIGHLIGHTS

- Experimental results for GFRP reinforced and GFRP encased concrete specimens are summarised.
- The procedure of determining the P-M interaction diagrams for the tested specimens is proposed.
- A parametric study was conducted for the interaction diagram of GFRP reinforced specimens.

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ABSTRACT

Fiber reinforced polymer (FRP) pultruded materials are available in a wide variety of shapes, including bars, I-sections, C-sections and other structural sections. Due to their high durability, low self-weight and reduced maintenance costs, these FRP materials are becoming a competitive option for replacing steel as structural materials especially in corrosive environments. This paper summarizes an experimental program on the axial and flexural behaviour of square concrete members reinforced with glass fiber reinforced polymer (GFRP) bars and embedded with pultruded GFRP structural sections under different loading conditions. Furthermore, an analytical model is presented to predict the axial load-bending moment interaction diagrams of the experimentally tested specimens. It can be concluded from this study that the analytical models provide reliable estimates of the maximum load and bending moment capacities of GFRP reinforced and GFRP encased concrete columns. In addition, a parametric study was conducted to study the effects of concrete compressive strength and longitudinal GFRP reinforcement ratio on the structural performance of GFRP reinforced square concrete columns.

1. Introduction

The use of reinforcement with FRP composite materials have emerged as one of the alternatives to steel reinforcement for concrete structures prone to corrosion issues. Currently, design standards have been developed for FRP reinforced flexural members, including ACI 440.1R-15 [1]. On the other hand, the level of understanding of the behaviour of FRP reinforced compression members has not reached a level where design standards are available for such members. Having said this, the current ACI 440.1R-15 [1] design guideline mentions to neglect the compressive contribution of FRP reinforcement when used as reinforcement in columns, in compression members, or as compression reinforcement in flexural members. Therefore, the acceptance of FRP by designers requires the development of design guidelines for the design of FRP bars in compression members such as columns. In this regard, limited experimental and analytical studies have been conducted to understand the compressive behaviour and failure modes of concrete columns internally reinforced with FRP and subjected to different loading conditions as discussed herein.

Kawaguchi [2] conducted an experimental study of twelve concrete specimens reinforced with aramid fiber-reinforced polymer (AFRP) bars. The specimens were tested in eccentric compression or tension. This study reported that the AFRP reinforced columns can be analysed using the same approach undertaken for concrete columns reinforced with steel bars. Choo et al. [3] reported that unlike steel reinforced columns, FRP reinforced columns interaction diagrams do not experience balance points due to the linear elastic material properties of the FRP bars until failure. Furthermore, FRP reinforced columns have a tendency to exhibit a failure point before the strength interaction reaches a pure bending condition, which is classified as brittle-tension failure due to the tensile rupture of the FRP bars. They reported that this failure occurs

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when low reinforcement ratios are considered. Therefore, Choo et al. [4] presented a set of equations for rectangular columns subjected to pure bending, to calculate the minimum FRP reinforcement ratio to prevent the tensile failure of the FRP bars in the tension side. Zadeh and Nanni [5] developed interaction diagrams for GFRP reinforced columns subjected to combined flexural and axial loads by assuming the GFRP longitudinal bars are only effective in tension. Therefore, compression GFRP bars were replaced by an equivalent area of concrete. Furthermore, the authors suggested imposing a limit of 1% on the maximum design tensile strain of GFRP longitudinal bars in order to avoid exaggerated deflections. In another study, Hadi et al. [6] tested circular concrete columns reinforced with GFRP bars and helices under concentric and eccentric loading conditions. The load carrying and bending moment capacities of the GFRP reinforced specimens were calculated analytically with the same principles used for conventional steel reinforced specimens and were compared with the experimental results.

The alternative use of FRP structural profiles and tubes in concrete members presents a very interesting potential, either for rehabilitation of existing structures or for new construction due to their many advantages including low self-weight, ease of installation, low maintenance costs and corrosion resistance. However, FRP profiles generally have low in-plane moduli and wall slenderness making them particularly vulnerable to local buckling. Tomblin and Barbero [7] reported that the strength of short columns made of GFRP I-sections are governed by local buckling, while Zureick and Scott [8] concluded that the failure mechanism of long columns is by global buckling. There have been several studies aimed to examine the structural advantages of connecting GFRP pultruded profiles to concrete compression and flexural elements to make better use of the profiles [9,10]. However, the encasement of GFRP structural sections in concrete columns has only been studied by Hadi and Youssef [11].

This study is a continuation of the experimental study of Hadi and Youssef [11] in which an experimental program investigating the behaviour of GFRP reinforced and GFRP encased concrete columns and beams was presented. Parameters investigated included the magnitude of load eccentricity and type of internal reinforcement with steel reinforced, GFRP reinforced, GFRP I-section encased and GFRP C-sections encased concrete specimens tested under compressive and flexural loading. This paper presents an analytical model to predict the load-interaction diagrams of GFRP reinforced and GFRP encased square concrete specimens and attempts to theoretically validate the experimental results of Hadi and Youssef [11].

2. Experimental program

2.1. Design of specimens

The experimental component of this study involved testing four groups of four square reinforced concrete columns under concentric as well as combined axial and flexural loading. The first group of specimens were reinforced with steel bars (Group RS) and the second group of specimens were reinforced with GFRP bars (Group RF). The first two groups of specimens were designed to have similar longitudinal and transverse reinforcement ratios. The longitudinal reinforcement ratio of the Group RS and Group RF specimens were 1.03 and 1.15%, respectively. The third (Group I) and fourth group (Group C) of specimens were encased with a pultruded GFRP I-section and C-sections, respectively. Each specimen had a square cross section with a side dimension of 210 mm and a height of 800 mm. The reinforcement details of all the groups of specimens are shown in Fig. 1. Each group consisted of four specimens; one specimen was tested concentrically, one tested under 25 mm eccentricity, one tested under 50 mm eccentricity and the last specimen was tested as a beam under four point loading test. The specimens are identified by the type of internal reinforcement and magnitude of load eccentricity. For example, Specimen RS-25 is reinforced with steel bars and is eccentrically loaded at 25 mm from the centreline. The letter "B" denotes a beam specimen tested under flexural loading.

A detailed discussion of the design, preparation, testing and instrumentation of the specimens is discussed in Hadi and Youssef [11].

2.2. Preliminary testing

In this study, all the concrete specimens were cast on the same day. The average compressive strength of the concrete (f'_c) at 28 days was determined to be 29.3 MPa. Furthermore, the average compressive strength of concrete at the first day and last day of testing the specimens was 31 MPa and 35.3 MPa, respectively. The compressive strengths were obtained by testing cylinders having a diameter of 100 mm and height of 200 mm, with five cylinders tested for each the 28 day and last day of testing and three cylinders tested on the first day of testing to obtain an average value for each day of testing.

Deformed steel N12 bars were used as longitudinal reinforcement in Group RS specimens. Five samples were tested in accordance with AS 1391-2007 [12] to determine the tensile properties of the reinforcing steel bars. The average yield stress (f_{sy}), yield strain (ε_{sy}) and modulus of elasticity (E_s) were determined to be 540 MPa, 0.324% and 200 GPa, respectively. Sand coated No. 4 (#4) GFRP bars of 12.7 mm standard diameter were used to reinforce the Group RF specimens longitudinally. The GFRP bars were manufactured by Pultrall Inc. [13]. Five samples were tested in accordance with ASTM D7205-11 [14] to determine the tensile properties of the GFRP bars. The ultimate tensile stress, corresponding rupture strain and tensile modulus of elasticity were 1641 MPa, 2.41% and 67.9 GPa, respectively. These properties were calculated based on the bar's standard diameter of 12.7 mm which was provided by the manufacturer [13].

GFRP pultruded I-sections and C-sections were used in the specimens of Group I and C, respectively and they were supplied by GRP Australia [15]. The tensile properties of the GFRP pultruded sections were determined based on the test method ISO 527-4-1997 [16] and are shown in Table 1. Five coupon samples from each GFRP C-section, web of the I-section and flange of the I-section were extracted in the longitudinal direction using a wet saw machine. The coupons had nominal dimensions of 300 mm long and 25 mm wide and were tested using a screw-driven material testing machine known as the 500 kN Instron 8033 machine. The compressive properties of the GFRP pultruded sections were determined based on the test method of ASTM D695-15 [17], as shown in Table 1. A total of 17 coupon samples from each web of the GFRP C-section, web of the I-section and flange of the I-section with nominal dimensions of $9.5 \times 12.7 \times 37.6$ mm were extracted in the longitudinal direction using a wet saw machine from the sections. To compensate for levelling errors, either the top and bottom ends of the coupons were levelled with a mill and/or the coupons were placed on a spherical seat. The coupons were tested under compression by direct end loading using the Instron 8033 machine, as shown in Fig. 2. Nine samples from the C-section and eight samples each from the web and flange of the I-section were instrumented with strain gauges to measure the elastic modulus in compression. The test method includes coupon dimensions for strength and modulus measurements. For the purposes of this study the dimensions required for modulus measurements was utilized.