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Analytical and experimental flexural behavior of concrete beams reinforced with glass fiber reinforced polymers bars

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HIGHLIGHTS

- Glass fiber reinforced polymers (GFRP) bars were produced in the lab.
- Ten half-scale concrete beams were tested to study flexural behavior.
- Crack widths, deflection, mode of failure and GFRP bar strains were discussed.
- Non-linear finite element analyses was performed and assessed with experimental results.
- Amendments to ACI 440-06 formula for predicting (I_e) were introduced.

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ABSTRACT

This paper presents an experimental, numerical and analytical study of the flexural behavior of concrete beams reinforced with locally produced glass fiber reinforced polymers (GFRP) bars. Glass fiber reinforced polymers (GFRP) reinforcement bars has a lower stiffness than steel reinforcement, which should be accounted for the ultimate and serviceability conditions, including the impact on member deflection and crack widths. The bars are locally produced by double parts die mold using local resources raw materials. A total of ten beams, measuring 120 mm wide × 300 mm deep × 2800 mm long, were cast and tested up to failure under four-point bending. The main parameters were reinforcement material type (GFRP and steel), concrete compressive strength and reinforcement ratio (μ_b, 1.7 μ_b and 2.7 μ_b; where μ_b is the reinforcement ratio at balanced condition). The mid-span deflection, crack width and GFRP reinforcement strains of the tested beams were recorded and compared. The test results revealed that the crack widths and mid-span deflection were significantly decreased by increasing the reinforcement ratio. The ultimate load increased by 47% and 97% as the reinforcement ratio increased from μ_b to 2.7 μ_b. Specimens reinforced by 2.7 μ_b can produce some amount of ductility provided by the concrete. The recorded strain of GFRP reinforcement reached to 90% of the ultimate strains. A non-linear finite element analysis (NLFEA) was constructed to simulate the flexural behavior of tested beams, in terms of crack pattern and load deflection behavior. It can be considered a good agreement between the experimental and numerical results was achieved. Modifications to ACI 440.1R-06 equation for estimating the effective moment of inertia (I_e) of FRP-reinforced concrete beams, using regression analysis of experimental results, is proposed by introducing empirical factors that effectively decrease the I_e at high load level. The proposed equation is compared with different code provisions and previous models for predicting the deflection. It can proved that the proposed factors gives good estimation for the effective moment of inertia (I_e) works well for FRP-reinforced concrete beams at high load level.

1. Introduction

Steel reinforcement corrodes rapidly under aggressive conditions such as marine environments. The corrosion is caused by chloride ions, which can be found in de-icing salts in northern climates and sea water along coastal areas. Other materials, such as Fiber Reinforced Polymers (FRP), have emerged as an alternative to steel reinforcement when the exposure situation of the RC member requires durability under aggressive conditions. FRP products are composite materials consisting of a matrix (resin) and reinforcing fibers. The fibers are stronger than the matrix. In order to provide the reinforcing function, the fiber-volume fraction should be more than 55 percent for FRP bars and rods [21]. FRP materials

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are anisotropic and are characterized by high tensile strength with no yielding only in the direction of the reinforcing fibers. This anisotropic behavior of GFRP bars affects the shear strength and dowel action as well as their bond performance [23]. The most common types of fibers are carbon, glass, and aramid. Glass fiber reinforced polymers (GFRP) bars have linear stress–strain behavior under tension up to failure; however, they have lower modulus of elasticity and no ductility like the steel bars. Therefore FRP reinforcement is not recommended for moment resistance frames or zones where moment redistribution is required [25].

The flexural behavior of concrete members reinforced with glass fiber-reinforced polymer (GFRP) reinforcing bars experimentally investigated by a number of studies [13,26,19,27]. They accounted for variations in concrete strength f_c', reinforcement ratio ρ, FRP bars type, and shear span-depth ratio (a_v/d). It was found that the ACI 440.1R model overestimate the effective moment of inertia. They proposed modifying Branson's original equation for the effective moment of inertia and introduced modification factors for FRP-RC members. Abdul Rahman and Narayan [1] analyzed the performance of the beams in terms of their load carrying capacity and found that beams reinforced with GFRP bars experienced 3 times larger deflection at the same load level compared with steel reinforced beam. In addition, Balendran et al. [12], concluded that the ultimate strength of sand coated GFRP reinforced specimens was 1.4–2.0 times greater than that of the mild steel reinforced specimens but exhibited a higher deflection. The design of FRP-reinforced concrete beams is usually governed by the serviceability limit state requirements (crack width and deflection criteria) rather than ultimate limit state requirements [22]. Consequently, a modified expression is needed to predict the expected service load deflections of FRP-reinforced members with a reasonably high degree of accuracy.

The aims of this paper are, firstly, to produce GFRP bars using the available raw material in the local market, secondly, to present results of an experimental study of concrete beams reinforced with locally produced GFRP bars in terms of the deflection behavior, cracking, and ultimate load carrying capacity. Three different amounts of GFRP reinforcement and three grades of concrete compressive strength were used for that purpose. Numerical models using nonlinear finite element analysis (NLFEA) were conducted to evaluate the beams behavior by ANSYS software. In addition, analytical models for predicting the deflection of FRP-reinforced concrete beams are compared with experimental results. This comparison showed a need for reliability analysis of FRP codes equations for calculating the deflection. Modified equation that correlates well with experimental results was introduced. Regression analysis is used in order to bridge the gap between the experimental results and the calculated values.

2. Test program

2.1. Glass FRP reinforcement bars manufacturing and testing

The test program is a part of an extensive research project that was carried out to study the behavior of concrete beams reinforced with GFRP bars [6]. The GFRP bars were manufactured by the authors using glass fiber roving and resin. Double sets of plastic mold were manufactured at private workshop to manufacture 2.80 m long GFRP bars with 12 mm diameter. The GFRP ribbed bar of 12 mm diameter and double sets of plastic mold are shown in Fig. 1. The cross-sectional area and equivalent diameter of the GFRP bars were determined using the test method B.1 from (ACI 440.3R-04) [3]. Tensile and modulus properties were determined according to ASTM Standard (ASTM D7205-06) [11]. Nine tension coupons were tested to determine the failure stress and modulus of elasticity. The tensile stress of GFRP bars was determined as the average tensile strength of the GFRP bar specimens of diameter 12 mm and was found to be 640 MPa.

2.2. Test specimens

Ten GFRP RC beams were designed as simple span, with an adequate amount of longitudinal and shear reinforcement to fail by either tensile failure by rupture of GFRP bars or crushing of concrete in the central zone. Additionally, one RC beam with similar amount of steel reinforcement to one type of the GFRP RC elements was tested as a control beam for comparison purposes. Two 8 mm GFRP rebar were used as top reinforcement to hold stirrups. Three different amounts of longitudinal reinforcement ratios (μ_b, 1.7 μ_b and 2.7 μ_b; where μ_b is the reinforcement ratio at balanced condition based on Eq. (5–3) [18], and three different concrete grades (25, 45, and 70 MPa) were used. Standard compressive-strength tests of twelve concrete cubes (158 mm × 158 mm × 158 mm) were performed using a MTS-200 testing machine for each concrete grade respectively. The steel reinforced concrete beam was designed to behave with the same cracked stiffness as the GFRP RC element with concrete compressive strength of 25 MPa and reinforced with ratio of 2.7 μb. The beam tests layout is detailed in Fig. 2.

Details of the tested beams are summarized in Table 1. The beam types were identified as A-yy-z. The first term of the identification corresponded to a beams group. The second parameter identifies the beam series, characters 25 denoted that a target concrete strength of the series is 25 MPa, whilst 45 and 70 denoted that a target concrete strength of the series is 45 MPa and 70 MPa respectively. The last term indicates the specimen reinforcement, identification 1 for reinforcement ratio equal μ_b, identification 2 for reinforcement ratio equal 1.7 μ_b, and identification 3 for reinforcement ratio equal 2.7 μ_b.

2.3. Test setup

The specimens were tested under four-point bending, with 2500 mm effective span, and 1100 mm shear span, the distance between loads being 300 mm. Each specimen was supported on roller assemblies and knife edges to allow longitudinal motion and rotation. Fig. 3 shows the test setup and instrumentations for tested specimen. Two linear variable differential transformers (LVDT) were installed horizontally at the center of the specimen in the constant moment region to measure the neutral axis depth. Electrical resistance strain gauges were applied to the GFRP bars to measure the strain during the tests. The strain gages, electrical pressure sensors, and (LVDTs) voltages were fed into the data acquisition system. Each specimen was loaded in 30–70 increments. The cracks of the specimens were mapped and test observations were recorded during loading and at the time of failure. Fig. 4 shows the crack growth of specimen A25-3.

3. Test results and discussion

During the test, the beams were observed visually until the first crack appeared and the corresponding load was recorded. The first cracking load was also verified from the load deflection and load–strain relationships. Table 2 provides a summary of the key experimental results for all beam specimens. The average initial cracking load of series A25 beams is 10.55 kN. The cracking load is directly related to concrete tensile strength which, in turn, is a function of compressive strength, increasing the concrete compressive strength is expected to yield higher cracking loads. The average initial cracking load of the series A45 and A70 beams are 16.25 kN