Construction and Building Materials 102 (2016) 574–591

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Experimental and analytical shear evaluation of concrete beams reinforced with glass fiber reinforced polymers bars

Mohamed Said, Maher A. Adam, Ahmed A. Mahmoud, Ali S. Shanour *

*Department of Civil Engineering, Shoubra Faculty of Engineering, Benha University, 108 Shoubra St., Shoubra, Cairo, Egypt*

## HIGHLIGHTS

- Glass fiber reinforced polymers (GFRP) bars were lab produced using local resources.
- Shear capacity, deflection, GFRP stirrups/bars strains were recorded and discussed.
- New approach to calculate FRP stirrups shear strength was proposed and verified.
- Non-linear finite element analyses was performed and assessed with experimental results.
- The shear capacities were calculated using the Strut and Tie Models (STM).

ARTICLE INFO

*Article history:*
Received 18 June 2015
Received in revised form 11 October 2015
Accepted 28 October 2015

*Keywords:*
Concrete beams
GFRP stirrups
Shear
Strut and tie models (STM)
Non-linear finite element analysis (NLFEA)

ABSTRACT

This paper presents an experimental and analytical study on the shear behavior of concrete beams reinforced with lab produced glass fiber reinforced polymers (GFRP) bars and stirrups. The bars and stirrups are manufactured by double parts die mold using local resources raw materials at lab. A total of ten beams measuring 120 mm wide, 300 mm deep and 1550 mm long were casted and tested up to failure under four-point load. The main parameters were concrete compressive strength and the vertical GFRP web reinforcement ratio in the form of the number of GFRP stirrups (without stirrups and with 8 @ 215, 8 @ 150 and 8 @ 100 stirrups). The mid-span deflection, inclined crack load and GFRP reinforcement bars and stirrups strains of the tested beams were recorded and compared. The test results revealed that the shear capacity increasing by 41% and 82% of the shear carrying capacity of beam without stirrups by using web GFRP reinforcement of 8 @ 215 and 8 @ 100 respectively. The shear capacity increased by 49% and 104% as the concrete compressive strength increased from 25 MPa to 45 MPa and 70 MPa respectively. The maximum value of measured strain in GFRP stirrups reached 0.0095. New approach to calculate FRP stirrups shear strength was proposed and verified throughout an assessment of experimental results of current study and previous works. The shear capacities of the tested specimens were calculated using the strut and tie models (STM) and non-linear finite element analysis (NLFEA). The average ratio of experimental shear capacity to calculated ($V_{exp}/V_{pred}$) using NLFEA and STM were 1.2 and 0.9 respectively.


## 1. Introduction

An innovative solution to the corrosion problem is the use of fiber-reinforced polymer (FRP) as an alternative reinforcing material in concrete structures. In addition to the non corrodible nature of FRP materials, they also have a high strength-to-weight ratio that makes them attractive as reinforcement for concrete structures. The location of the stirrups at the outer face of concrete elements makes more vulnerable to harsh environmental effects, which accelerate the deterioration process and reduce the service life of the structure. Consequently, the use of FRP materials as an alternative shear reinforcement in reinforced concrete structures is becoming a more conventional countermeasure in structural members subjected to harsh environmental exposure. FRP products are composite materials consisting of a matrix (resin) and reinforcing fibers which are stronger than the matrix. To provide the reinforcing function, the fiber-volume fraction should be more than 55 percent for FRP bars and rods as recommended by many guidelines (ISIS Manual No.3 2007). The anisotropic behavior of FRP composites can be characterized by high tensile strength with no yielding only in the direction of the reinforcing fibers. This

* Corresponding author.
*E-mail addresses:* mohamed.abdelghaffar@feng.bu.edu.eg (M. Said), maher.adam@feng.bu.edu.eg (M.A. Adam), ahmed.m5882@gmail.com (A.A. Mahmoud), ali.shnor@feng.bu.edu.eg (A.S. Shanour).

http://dx.doi.org/10.1016/j.conbuildmat.2015.10.185
0950-0618/

behavior affects the shear strength, dowel action and their bond performance, Nanni [21].

When using FRP as shear reinforcement, it is essential to be aware of that: FRP has a relatively low modulus of elasticity; FRP has a high tensile strength and no yield point; tensile strength of the bent portion of an FRP bar is significantly lower than the straight portion; and FRP has low dowel resistance. Most of the shear design provisions incorporated in the codes and guides were based on the design formulas of members reinforced with conventional steel considering some modifications to account for the substantial differences between FRP and steel reinforcement. These provisions used the well-known $V_c + V_f$ method of shear design, which is based on the truss analogy. Revision of the concrete shear strength of members longitudinally reinforced with FRP bars, $V_{cf}$, is presented below.

The aims of this paper is to present results of an experimental study of concrete beams reinforced with GFRP bars and vertical GFRP stirrups in terms of the ultimate shear carrying capacity. Three different amounts of GFRP web reinforcement and three grades of concrete compressive strength were used for that purpose. Assessment of experimental results of current study and from previous works was performed to enhance the formula that calculates FRP stirrups shear strength. Therefore, new approach was proposed and verified. Numerical models using nonlinear finite element analysis (NLFEA) were conducted to evaluate the beams behavior by ANSYS software. In addition, the shear capacities of the tested specimens were calculated using the Strut and Tie models (STM). The computer software program, Computer Aided Strut-and-Tie, (CAST, Ver. 0.9.11) was used to calculate the shear capacity of tested specimens.

## 2. Analytical models for shear resistance of FRP reinforced beams

Different models for the concrete shear capacity of FRP reinforced concrete beams, $V_{c,f}$ are shown in Table 1. ECP 208 [11] and ACI 440.1R-03 Design Guidelines [3], evaluated the concrete shear capacity $V_{c,f}$ of flexural members using FRP as main reinforcement. The equations depicted in Table 1, accounts for the axial stiffness of the FRP reinforcement ($A_fE_f$) as compared to that of steel reinforcement ($A_sE_s$). Where $\rho_f$ and $\rho_s$ are the reinforcement ratios of the flexural FRP and steel reinforcement, respectively, $E_f$ and $E_s$ are the modulus of elasticity of FRP and steel reinforcement, respectively, and $V_c$ is the design shear strength provided by the concrete for the steel reinforced section. The shear resistance provided by FRP stirrups perpendicular to the axis of the member $V_f$ is presented in Table 1. In this equation, the tensile strength of FRP stirrups expressed as a fixed ratio of the modulus of elasticity of FRP stirrups and should not exceed $f_{fb}$. The design tensile strength of FRP bars at a bend, $f_{fb}$ depends on the radius of the bend, $r_b$, diameter of reinforcing bar, $d_b$ and design tensile strength of FRP, $f_{fu}$.

ACI 440.1R-06 [4], addressed the shear resistance of FRP reinforced beams with the hypothesis of that the dowel action contribution of FRP longitudinal reinforcements is less than that of an equivalent steel area. The concrete shear capacity $V_c$ of flexural members using FRP as main reinforcement is shown in Table 1, where $b_w$ is the width of the web, $c$ is the cracked transformed section neutral axis depth, $\rho_f$ is FRP reinforcement ratio and $n_f$ is the modular ratio. ISIS Canada [15], stated that the shear resistance attributed to concrete, $V_{cf}$, of members reinforced with FRP bars as flexural reinforcement is calculated according to the same principles as for steel reinforced concrete (CSA A23.3-94) after accounting for the difference in the modulus of elasticity between FRP and steel reinforcement as given in Table 1. CAN/CSA S806-02 [10] and JSCE [16] calculated the concrete contribution to shear strength using the Equations shown in Table 1. El-Sayed et al. [13], found that the ratio of concrete shear strength of concrete beams reinforced with FRP bars to that of beams reinforced with steel ($V_{c,f}/V_c$) is proportional to the cube root of the axial stiffness ratio between FRP and steel reinforcing bars $\left(\sqrt[3]{\rho_f E_f / \rho_s E_s}\right)$. They applied this finding to the ACI 440.1R-03 shear design equation; therefore, give new equation as depicted in Table 1. This equation was verified against experimental shear strengths of 98 specimens tested to date, and the calculated values were shown to compare well. Wegian et al. [30] introduced a simplified expression for the shear capacity of FRP reinforced concrete member, as given in Table 1.

**Table 1**
Different equations for the shear resistance of FRP-reinforced beams.

| Reference | Model |
|---|---|
| ACI 440.1R-03 Design Guidelines [2] and ECP 208 [11] | $V_{c,f} = \frac{\rho_f E_f}{\rho_s E_s} V_c$<br>$V_f = \frac{A_{fv} f_{fv} d}{s}$<br>where $f_{fv} = 0.004E_f \leqslant f_{fb}$ (ACI 440.1R-03)<br>$f_{fv} = 0.002E_f \leqslant f_{fb}$ (ECP 208 [11])<br>and $f_{fb} = \left(0.05 \cdot \frac{r_b}{d_b} + 0.3\right) f_{fu} \leqslant f_{fu}$ |
| ACI 440.1R-06 Design Guidelines [4] | $V_c = \frac{2}{5}\sqrt{f'_c} b_w c$<br>where $c = k\,d$ and $k = \sqrt{\rho_f n_f + \left(\rho_f n_f\right)^2} - \rho_f n_f$ |
| ISIS Canada [15] | $V_{c,f} = 0.2\lambda\phi_c\sqrt{f'_c} b_w d\sqrt{\frac{E_{frp}}{E_s}}$<br>$V_{c,f} = \left[\frac{260}{100+d}\right]\lambda\phi_c\sqrt{f'_c} b_w d\sqrt{\frac{E_{frp}}{E_s}} \geqslant 0.1\lambda\phi_c\sqrt{f'_c} b_w d\sqrt{\frac{E_{frp}}{E_s}}$ |
| CAN/CSA-S806-02 [10] | $V_{c,f} = 0.035\lambda\phi_c\left(f'_c \rho_f E_f \frac{V_f}{M_f} d\right)^{1/3} b_w d$<br>Such that: $0.1\lambda\phi_c\sqrt{f'_c} b_w d \leqslant V_{c,f} \leqslant 0.2\lambda\phi_c\sqrt{f'_c} b_w d$<br>$\frac{V_f}{M_f} d \leqslant 1.0$ |
| JSCE [16] | $V_{c,f} = \beta_d \beta_p \beta_n f_{cvd} b_w d/\gamma_b$<br>where $f_{cvd} = 0.2\left(f'_{cd}\right)^{1/3} \leqslant 0.72\ \text{N/mm}^2$<br>$\beta_d = (1000/d)^{1/4} \leqslant 1.5$<br>$\beta_p = \left(100\rho_f E_f/E_s\right)^{1/3} \leqslant 1.5$<br>$\beta_n = 1 + M_o/M_d \leqslant 2$ for $N'_d \geqslant 0$<br>$\beta_n = 1 + 2M_o/M_d \geqslant 0$ for $N'_d < 0$ |
| El-Sayed et al. [13] | $V_{c,f} = 0.037\left(\frac{\rho_f E_f \sqrt{f'_c}}{\beta_1}\right)^{1/3} b_w d \leqslant \frac{\sqrt{f'_c}}{6} b_w d$<br>where $0.85 \geqslant \beta_1 = 0.85 - 0.007(f'_c - 28) \geqslant 0.65$ |
| Wegian et al. [30] | $V_c = 2\left(f'_c \cdot \frac{\rho E_f}{E_s} \cdot \frac{d}{a}\right)^{1/3} b_w d$ |

## 3. Test program

### 3.1. 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, Shanour [5]. The GFRP bars were manufactured by the authors using glass fiber roving and resin. Previous work was tested for flexural specimens with lab produced GFRP bars [19]. Double sets of plastic mold were manufactured at lab to manufacture 1.55 m long GFRP bars with 12 mm diameter and stirrups with diameter 8 mm. The GFRP ripped bar of 12 mm diameter and 8 mm stirrups 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). Tensile and modulus properties were determined according to ASTM Standard (ASTM D7205-06) [8]. Nine tension coupons were tested to determine the failure