Composites: Part B 43 (2012) 2125–2134

Contents lists available at SciVerse ScienceDirect

Composites: Part B

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

Deflection behaviour of FRP reinforced concrete beams and slabs: An experimental investigation

Raed Al-Sunna [a], Kypros Pilakoutas [a], Iman Hajirasouliha [b,*], Maurizio Guadagnini [a]

[a] Department of Civil & Structural Engineering, The University of Sheffield, Sheffield, UK
[b] Department of Civil Engineering, The University of Nottingham, Nottingham, UK

ARTICLE INFO

Article history:
Received 11 June 2011
Received in revised form 25 February 2012
Accepted 10 March 2012
Available online 19 March 2012

Keywords:
A. Carbon fibre
A. Glass fibre
C. Analytical modelling
D. Mechanical testing
Deformation behaviour

ABSTRACT

The flexural response of FRP RC elements is investigated through load–deflection tests on 24 RC beams and slabs with glass FRP (GFRP) and carbon FRP (CFRP) reinforcement covering a wide range of reinforcement ratios. Rebar and concrete strains around a crack inducer are used to establish moment–curvature relationships and evaluate the shear and flexural components of mid-span deflections. It is concluded that the contribution of shear and bond induced deformations can be of major significance in FRP RC elements having moderate to high reinforcement ratios. Existing equations to calculate short-term deflection of FRP RC elements are discussed and compared to experimental values.

1. Introduction

FRP reinforcement for concrete has been developed to replace steel in special applications, particularly in corrosion-prone RC structures. Under similar conditions, in terms of concrete strength, applied loading, member dimensions and area of reinforcement, FRP RC members are expected to develop larger deformations than steel reinforced members [1]. This can be mainly attributed to the lower modulus of elasticity of the FRP rebars, but also to their unique bond characteristics. As a result, the design of FRP RC elements is often governed by the serviceability limit state [2]. Accurate calculation of service deflections can be done through integration of curvatures [3,4] and making allowance for shear and bond deformations. However, such calculations are time consuming and not suitable for design. It is therefore important to develop simplified design methods to evaluate the deflection of RC elements with an acceptable accuracy. The implementation of simple elastic analysis models, along with the use of an effective moment of inertia to describe the reduced stiffness of a cracked element, has proven effective in determining service deflections of steel reinforced concrete elements and has also been adopted for FRP reinforced concrete elements. ACI 440.1R-06 [5], for example, has adopted a modified form of the effective moment of inertia equation included in ACI 318 [6] and originally developed by Branson [7]. Although a similar model is also discussed in the design manual published by ISIS Canada [8], the use of an equation derived by implementing the tension stiffening effect included in Model Code 90 [3] is proposed as a more reliable model for concrete elements reinforced with different types of FRP reinforcements. The tension stiffening model of Model Code 90 also underlies the method recommended in Eurocode 2 [9] to estimate service deflections for steel RC elements, and was shown to lead to acceptable results also for FRP RC elements [4]. CAN/CSA-S806 [10] recommends determining deflections by integration of curvatures along the span, but ignores the tension stiffening effect provided by the FRP reinforcement. Instead it proposes the use of a gross and cracked moment of inertia to represent the stiffness of uncracked and cracked portions of the element, respectively.

Although the code approaches for the prediction of short-term deflection account for a reduced flexural stiffness of the element due to cracking [11], this effective stiffness is treated as a global parameter and cannot capture the effect of localized cracking. As a result, the deflection derived using only cracked moment of inertia is expected to provide an upper bound limit for short-term deflections. However, tests on beams and slabs [12–14] show that deflections tend to exceed this upper bound even at relatively low load levels.

Shrinkage related phenomena have also been shown to affect the deformation behaviour of an RC element to a certain extent [15]. Depending on the level of shrinkage, the tensile restraining forces imposed by the bonded reinforcement can cause the development of tensile strain in the surrounding concrete, and shrinkage-induced curvatures can develop as a result of the eccentricity of these

* Corresponding author.
E-mail address: i.hajirasouliha@nottingham.ac.uk (I. Hajirasouliha).

1359-8368/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2012.03.007

restraining forces. Shrinkage induced curvatures mainly develop prior to the test. The presence of an initial non-zero state of strain in the concrete can result in a reduction of the imposed moment required to cause cracking. Shrinkage, if significant, could also affect the flexural deformations during loading tests. However, even by adopting the shifting of cracked moment of inertia approach by Bischoff and Johnson [15], some of the additional deflections measured in the tests cannot be justified [16]. Furthermore, the authors believe that the pre-compression effect from shrinkage on the bar will not affect the cracked stiffness, and therefore, will not greatly influence the overall load-deformation behaviour after cracking.

Materials and geometrical nonlinearity, along with the degradation of the sectional composite behaviour, also contribute to increase the total deformation of an RC element, and their effect is particularly significant at high load levels. The plane sections remain plain assumption of section analysis is considered true for flexural elements at the macro scale, but it does not necessarily apply in the regions around the crack. This may be amplified in the case of FRP RC since the neutral-axes depth can be very small. However, results from lightly steel reinforced concrete elements show that there are no significant additional deformations at least up to the point of yielding [16].

Mota et al. [17] and Rafai and Nadjai [18] examined several existing deflection models for FRP RC beams and slabs and concluded that their performance is highly dependent on the accuracy of the calculated cracking moment. The results of their study indicate that there is a critical need for reliability analysis of FRP code equations to develop more accurate load–deflection formulas for FRP RC members.

Despite extensive research on the behaviour of FRP RC members, less research has been conducted on deflection prediction of FRP RC elements considering the effects of different stress levels and reinforcement ratio (for example [19,20]). To examine these, an experimental study was undertaken to investigate the deflection behaviour of FRP RC concrete beams and slabs at serviceability and ultimate load levels. The experimental programme comprised twelve beams and twelve slabs with glass FRP (GFRP) and carbon FRP (CFRP) with a wide range of reinforcement ratios. The experimentally determined deflections are used to examine the accuracy of the predictive models discussed above and presented in detail in the following sections.

2. Deflection prediction of FRP RC elements

To calculate short-term deflections of FRP RC beams, ACI 440.1R-03 [21] adopted the following expression for effective moment of inertia (I_e), which accounts for the lower FRP modulus of elasticity (E_f) and different FRP bond characteristics.

$$I_e = I_{cr} + (\beta_d I_g - I_{cr})\left[\frac{M_{cr}}{M_a}\right]^3 \leqslant I_e \quad (1)$$

$$\beta_d = \alpha_b\left[\frac{E_f}{E_s} + 1\right] \quad (2)$$

where I_g and I_{cr} are the gross and cracked moment of inertia; M_{cr} and M_a are the cracking and applied moment; E_f and E_s are the FRP and steel modulus of elasticity respectively; and α_b is a bond dependent coefficient, which equals 0.5 for steel rebars. In the absence of more research data, a value of 0.5 has been recommended for all FRP rebar types. ACI 440.1R-06 [5] abandons the reliance of β_d on bond, and takes β_d as proportional to the ratio of reinforcement ratio (ρ_f) to the balanced reinforcement ratio (ρ_{fb}).

$$\beta_d = \frac{1}{5}\left(\frac{\rho_f}{\rho_{fb}}\right) \quad (3)$$

Using the balanced reinforcement ratio (ρ_{fb}) in this equation implies that deflection depends on the ultimate tensile stress of the FRP reinforcement.

After cracking, the composite action between the concrete and FRP rebars may not be as perfect as it is usually assumed [7,12]. In addition, shrinkage and the non-linear behaviour of concrete in the compression zone can affect the stiffness of an RC element [15]. To address this issue, a possible approach is to provide a transition between I_g and a certain fraction of I_{cr} in the calculation of I_e. Such an equation was proposed by Benmokrane et al. [12], but was calibrated using a limited number of tests .

$$I_e = \alpha_0 I_{cr} + \left(\frac{I_g}{\beta_0} - \alpha_0 I_{cr}\right)\left[\frac{M_{cr}}{M_a}\right]^3 \quad (4)$$

where α_0 and β_0 are equal to 0.84 and 7, respectively. Naturally, this equation offers more flexibility compared to the current ACI 440.1R-06 [5] equation. The factor α_0 can reflect the reduced composite action between the concrete and FRP rebars. The factor β_0 was introduced in the equation to enable a faster transition from I_g to I_{cr}, since the degradation in stiffness due to the 3rd power component was considered to be too low.

Bischoff [7] and Bischoff and Scanlon [22] analyzed extensively the ACI 318 [6] expression for I_e from a tension-stiffening standpoint. The results of their studies indicate that the ACI 318 [6] proposed method is not suitable for GFRP RC. The following equation was proposed for I_e, which is analogous to the equation that can be deduced by implementing the provisions of CEB-FIP Model Code 90 [3] to determine instantaneous curvatures or deflections. This equation is claimed to be equally applicable for FRP and steel RC beams.

$$I_e = \frac{I_{cr}}{1 - \eta\left(\frac{M_{cr}}{M_a}\right)^2} \leqslant I_g, \text{ and } \eta = 1 - \frac{I_{cr}}{I_g} \quad (5)$$

To predict the deformation of RC beam elements, Eurocode 2 [9] tries to account for the tension stiffening effect based on the CEB-FIP Model Code 90 [3] approach. Based on Eurocode 2 [8], the

Table 1
Tensile properties of GFRP and CFRP rebars.

Rebar type	Nominal diameter (mm)	Manufacturer modulus of elasticity (MPa)	Test modulus of elasticity (MPa)	Manufacturer guaranteed tensile strength (MPa)	Test tensile strength, (MPa)	
					Average	Standard deviation
GFRP	6.35	40800	38900	830	600	70
	9.53	40800	42800	760	665	35
	12.7	40800	41600	690	620	40
	19.05	40800	42000	620	670	10
CFRP	6.35	120000	133000	1450	1450	40
	9.53	123000	132000	1380	1320	170
	12.7	112000	119000	1230	1475	60