Composites Part B 85 (2016) 315–335

Contents lists available at ScienceDirect

Composites Part B

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

Utilization of hybrid approach towards advanced database of concrete beams strengthened in shear with FRPs

Theodoros C. Rousakis [a, *], Maria E. Saridaki [a], Soultana A. Mavrothalassitou [a], David Hui [b]

[a] *Laboratory of Reinforced Concrete, Department of Civil Engineering, Democritus University of Thrace (DUTh), 67100 Xanthi, Greece*
[b] *Composite Material Research Laboratory, Department of Mechanical Engineering, University of New Orleans, LA 70148, USA*

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form
21 August 2015
Accepted 22 September 2015
Available online 11 November 2015

Keywords:
A. Polymer–matrix composites (PMCs)
B. Strength
C. Analytical modeling
C. Statistical properties/methods
Shear

ABSTRACT

This paper concerns the shear behavior of reinforced concrete beams externally strengthened with composite materials. The study gathers numerous experiments on concrete beams, strengthened in shear with FRPs, from the international literature and develops an experimental database. The database is utilized to assess the predictive accuracy of significant existing design recommendations, with respect to the vertical load capacity of the tested beams. The crucial parameters for predicting the shear capacity of FRP strengthened beams are identified. Some of these parameters are disregarded in the reported results of several experimental programs or are difficult to measure. The research utilizes the available full load-deformation curves for numerous tests as well as the predictive accuracy and easy to apply modified compression field theory (MCFT). Reverse MCFT analysis of beams may provide significant information concerning the angle of main shear crack, the average crack width of concrete and the average effective deformation of the FRP and of internal steel, given the failure load. Thus, a hybrid approach is followed to enrich the experimental database with analytically derived significant parameters towards an advanced database. The hybrid experimental–analytical database is further elaborated and recent studies on shear behavior of concrete members are taken into account. The study explores the influence of different crucial parameters and proposes suitable modifications of existing design equations towards remarkably improved shear force resistance predictions.

1. Introduction

Externally bonded fiber-reinforced polymers (FRPs) have been established in construction in the late 1980s in Europe and Japan followed by the United States and Canada [8,4]. Early systematic research [9–23] in FRP-retrofitted reinforced concrete (RC) columns and beams revealed several key features of the technique over conventional reinforced concrete or steel jacketing. Certain advantages of FRP reinforcements, extensively discussed elsewhere (e.g., Refs. [1,24–27] among others), favored their increasing use over conventional materials in retrofitting.

Shear FRP retrofit may concern beams under static, fatigue or seismic loading. Most research is focused on static loading of beams with or without steel stirrup reinforcement [28–59]. Carbon FRP is the common choice in external shear FRP strengthening of RC members because of the high modulus of elasticity that results in thin jackets and effective restriction of the inclined tensile strains of concrete while achieves advanced durability performance. Yet, other materials are under investigation such as glass, aramid or PET FRP. Shear strengthening may concern fully wrapped, U-wrapped or side bonded detailing.

The extensive application of FRPs in construction is currently supported by various design recommendations and codes that refer among else to shear strengthening of concrete members (*fib* Bulletin 14 2001, CNR-DT 200/2004 2004, ACI 440.2 R-08 2008, The Concrete Society TR55 2012, DAfStb 2012 and Greek Retrofit Code 2013 [1–6]). All recommendations are based on the strut-and-tie model proposed by Mörsch (1909, 1922 [60,61]) and they generally belong to the category of modern truss models following smeared approaches in order to account for FRP contribution.

Among numerous smeared crack models, Vecchio and Collins (1986) [7] proposed the easy to apply modified compression field theory (MCFT). It takes into account equilibrium conditions, compatibility requirements and stress–strain relationships including the tensile stresses in the concrete between the cracks.

* Corresponding author. Department of Civil Engineering, Democritus University of Thrace, Vas. Sofias 12, 67100 Xanthi, Greece. Tel.: +30 2541079645.
E-mail address: trousak@civil.duth.gr (T.C. Rousakis).

http://dx.doi.org/10.1016/j.compositesb.2015.09.031
1359-8368/

Above relationships are expressed in terms of average stresses and average strains, based on numerous in-plane shear experiments with innovative and demanding test setup. The analytical approach considers the local stress conditions at crack locations as well. MCFT has proven its predictive accuracy in concrete members with significant shear effects considering reliable step-by-step flexure – shear (M–V) interaction.

The paper concerns the assessment and improvement of existing recommendations for shear design of reinforced concrete beams externally strengthened with composite materials. The study follows a hybrid experimental–analytical approach compatible with the main features of existing recommendations. Numerous experiments on FRP strengthened beams in shear, from the international literature, are gathered to form a solid database. The main design parameters – addressed in previous studies – are extensively investigated herein in a design oriented mode. Concrete shear contribution [32,62], contribution of existing internal steel stirrup in cases of FRP retrofit [50,52,63–68,49] and contribution of FRP retrofit [48,49,69,70,51,71–75] are thoroughly discussed. The vertical load capacity of the beams is calculated according to existing design recommendations and is compared against the experimental ones. The available experimental full P–d curves are further utilized and are compared against the analytical ones provided by MCFT. Thus, part of the original database is further enriched with averaged analytical values for the angle of main shear crack and for the effective deformation of the FRP and of the steel shear strengthening (given the failure load) to form a hybrid database. The study elaborates the available experimental results, the hybrid database as well as recent studies on shear behavior of RC members to improve the accuracy of existing design recommendations. It comes out that the contribution of concrete, of the angle of the main shear crack and of the effective deformation of the FRP at failure are highly influencing variables. The proposed improvements on existing recommendations reveal their potential to provide more accurate shear capacity predictions.

2. Experimental database

This paper gathers and elaborates experiments of RC beams from 38 experimental programs from the international literature [16,19–21,28–59,66,83] strengthened externally with fiber reinforced polymers (FRP) against shear failure. The database is formed through critical validation of available databases in literature by Refs. [28,53] against original-source-papers and further enrichment with experimental results up to 2015 (from 150 FRP strengthened specimens of previous databases to 217). It should be mentioned that the database of 217 specimens does not include unstrengthened beams. The database includes shear experiments with all characteristics of tested beams naming, the shape and dimension of the cross-section, mechanical characteristics of concrete and steel materials, volumetric ratio of steel stirrups and longitudinal bars (Table 1a). The database also contains the material properties of the FRP strengthening (CFRP, GFRP, aramid AFRP and PET FRP), its detailing, the FRP thickness, the number of layers, inclination of the sheets, shear span ratio and the experimental shear strength (Table 1b).

The collected experiments include beams with rectangular cross section (R, 181 specimens) or T-shaped section (T, 36 specimens) with dimensions of 70 × 110 mm to 250 × 500 mm and a shear span ratio ranging from 2.28 to 4.08. All specimens include longitudinal reinforcement with volumetric ratio varying between 0.01 and 0.08. Out of a total of 217 beams, 110 have internal transverse steel reinforcement (stirrups). The volumetric ratio of steel stirrups ranges between 0.0005 and 0.0044. Most of the tested beams are strengthened with carbon FRP (CFRP), while only 30 beams concern glass (GFRP, 10 specimens), aramid (AFRP, 12 specimens) or PET fibers (PET FRP, 8 specimens). The modulus of elasticity of FRPs varies between 5.3 GPa and 392 GPa. Most of the beams have full transverse FRP sheet strengthening (123 specimens) or discrete strips. The strips are applied vertical to the beam axis (188 specimens) or with an inclination of 45° (26 specimens) or 60° (3 specimens, Fig. 1). Finally, the beams are divided in three subcategories according to the detailing of FRP strengthening around the concrete cross section: fully wrapped (R, 53 specimens), U-wrapped (U, 95 specimens with FRP bonded to the three sides of the beam) and side bonded (S, 69 specimens with FRP bonded to the two opposite sides of the beam) as presented in Fig. 2. Four out of 217 tested beams included U wrapping, suitably anchored to be equivalent to R-type wrapping. For 61 beams the whole vertical load - deflection was available.

From the comparative study of the collective data for shear-critical beam members (developed shear stress surpasses the strength of concrete) the following main conclusions are cited:

a) successful design of shear reinforcement aims at limiting the opening of variable critical inclined cracks that lead to premature non-ductile beam failure (loss of carrying capacity before the yielding of longitudinal reinforcement and desirable curvature ductility of the beam),
b) the shear contribution of concrete is variable and affected by the size of the beams. It depends on the shear span of the beam as concluded in Zararis and Papadakis 2001 [62],
c) for inadequate shear strengthening, inclined cracks are formed. One out of the initial cracks opens widely and forms the major inclined crack. The beam fails with the crushing of the compression zone over the crack tip (*fib* bulletin 16, 2002 [76]).

3. Existing design recommendations for shear FRP strengthening

The experimental results of the 217 beams of the database are compared against the analytical predictions of the shear strength, according to significant existing guidelines: *fib* Bulletin 14 (2001), CNR-DT 200/2004 (2004), ACI 440.2 R-08 (2008), TR55 (2012), DAfStb (2012) and Greek Retrofit Code (GRECO, 2013) [1–6]. The main shear design equations of all recommendations under elaboration are listed in Table 2. All recommendations are based on the strut-and-tie model proposed by Mörsch (1909, 1922) [60,61]. Up to date, the basic strut-and-tie model has been developed to modern truss models following smeared approaches (*fib* 16, 2002 [76]). That is, the compression fields are modeled in most cases independently from the crack pattern. This, results in considering the principal stress axes and principal strain axes coincide. Above approximation is not consistent with the experimental behavior of concrete under general triaxial stress-state and several other approaches such as non-associative plasticity modeling deal with this (i.e. Rousakis et al. 2008 for triaxial compression [77]). Thus, most smeared approaches consider the compression field angle and the crack angle identical in shear problems. Another class of strut-and-tie models includes truss models with crack friction that follow a discrete approach for cracking (*fib* 16, 2002 [76]). In that case, the shape, the geometry and spacing of cracks is modeled in a way more consistent to fundamental shear behavior of concrete. The angles of the compression struts and of the crack angles are different while friction forces at cracks contribute to the shear transfer mechanisms. In an attempt to provide an enhanced smeared crack model, Vecchio and Collins (1986) [7] propose the MCFT that includes check of the friction at crack, based on the work by Walraven (1981) [78], while assuming for simplification that angles for compression