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Shear strengthening of RC beams with NSM CFRP laminates: Experimental research and analytical formulation

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ABSTRACT

The effectiveness of the NSM technique with CFRP laminates for the shear strengthening of RC beams with a certain percentage of steel stirrups was assessed by an extensive experimental research. In this context, the influence of the following parameters was investigated: concrete strength; percentage of existing steel stirrups; percentage and inclination of the CFRP laminates; existence of cracks when the RC beams are shear strengthened with NSM CFRP laminates. The results show that the higher is the concrete strength class the larger is the effectiveness of the NSM technique. The effectiveness of the CFRP laminates was higher in the beams with the lower percentage of steel stirrups. Inclined laminates were more effective than vertical laminates and the shear resistance of the beams has increased with the percentage of laminates. Pre-cracked RC beams shear strengthened with NSM CFRP laminates have presented a load carrying capacity similar to that of the homologous beams that were uncracked when strengthened. Taking the results obtained in the experimental research, an analytical formulation to predict the contribution of the possible distinct NSM shear strengthening configurations for the shear resistance of RC beams was developed. This analytical formulation is presented and its predictive performance is assessed.

1. Introduction

Using advanced composites materials like carbon fiber reinforced polymers (CFRPs), competitive structural strengthening solutions can be developed due to the high strength-to-weight ratio, high durability (non-corrodible), electromagnetic neutrality, ease of handling, rapid execution with low labor, and practically unlimited availability in size, geometry and dimension of these materials [1–3]. In consequence, the strengthening techniques based on the use of CFRP composites materials have been intensively investigated and applied in cases where they constitute solutions that compete with the traditional strengthening techniques applied in reinforced concrete (RC) structures.

A RC beam needs to be shear strengthened when is deficiently reinforced in shear, becomes subjected to higher loads, or when its shear capacity falls below its flexural capacity after have been submitted to a flexural strengthening intervention. The shear failure mode of a RC element should be avoided since it is brittle and unpredictable. Near surface mounted (NSM) with CFRP laminates is a technique that can be used for the shear strengthening of RC beams [4–6]. This technique involves the installation of narrow strips of CFRP laminates, of rectangular cross section, into thin slits open on the concrete cover of the lateral faces of the beams. The laminates are positioned orthogonally to the beam's axis, or as orthogonal as possible to the predicted direction of the shear failure crack, or to the already existing shear cracks.

Experimental research has demonstrated that the NSM technique provides higher strengthening effectiveness than the Externally Bonded Reinforcing (EBR) technique with CFRP [4,7]. This fact is derived from the larger ratio between the CFRP-concrete bond perimeter and the cross sectional area of the CFRP element in case of NSM, and is also caused by the confinement provided by the surrounding concrete to the CFRP laminate [7,8]. A further advantage of the NSM technique is its ability to significantly reduce the probability of harm resulting from acts of vandalism, mechanical damages and aging effects. When NSM is used, the appearance of a structural strengthened element is practically unaffected by the strengthening intervention.

To appraise the performance of the application of NSM CFRP laminates for the shear strengthening of RC beams having a certain percentage of existing steel stirrups, an extensive experimental research was carried out. Four series of tests with T cross section RC beams were executed with the purpose of evaluating the influence of the following parameters on the effectiveness of the NSM shear strengthening technique: concrete strength, percentage of existing steel stirrups, percentage and orientation of the CFRP laminates. The strengthening intervention often involves concrete elements already cracked. To evaluate the influence, on the strengthening effectiveness, of already existing cracks when a beam is shear

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strengthened with NSM CFRP laminates, some of the RC beams were pre-cracked prior to their strengthening. A detailed description of the carried out experimental research, and a discussion of the obtained results are done in the present paper. Considering the results obtained in the experimental research, an analytical formulation to predict the contribution of the NSM CFRP laminates for the shear capacity of a RC beam was developed. The analytical formulation is described and its predictive performance is assessed in this paper.

2. Experimental program

2.1. Test series

The experimental program is composed of four series of RC beams (series A, B, C and D). Fig. 1 represents the T cross section geometry and reinforcement detailment for each series, as well as the longitudinal geometry, loading configuration and support conditions. The general information of the tested series of beams is represented in Table 1. The adopted reinforcement systems were designed to assure shear failure mode for all the tested beams. To avoid shear failure in the L_r beam span (Fig. 1), in this span was applied steel stirrups of 6 mm diameter spaced at 75 mm (ϕ6@75 mm) in series A, B and C, and steel stirrups of 8 mm diameter spaced at 80 mm (ϕ8@80 mm) in series D. For each series, the differences between the tested beams are restricted to the shear reinforcement systems applied in the L_i beam span. As schematically represented in Fig. 1, the laminates were distributed along the AB line, where A represents the beam's support at its "test side" and B is obtained assuming load degradation at 45°.

A general analysis of the data of Table 1 shows that the tested beams had percentages of longitudinal tensile steel bars (ρ_{sl}) around 3% and had percentages of steel stirrups (ρ_{sw}) ranging between 0.10% and 0.17%. In terms of concrete, three types were basically used: concrete of low strength (f_{cm} = 18.6 MPa, where f_{cm} is the average concrete compressive strength at the age of the beams tests), concrete of medium strength (f_{cm} = 31.1/39.7 MPa) and concrete of high strength (f_{cm} = 59.4 MPa). Three orientations of the laminates with respect to the beam axis were tested, Fig. 1, (θ_f = 90° – vertical laminates; θ_f = 45° – laminates at 45°; θ_f = 60° – laminates at 60°), and the levels of the CFRP percentage (ρ_f) analyzed ranged between 0.06% and 0.19%. The monitored beam span (L_i) was 2.5 times the effective depth of the beam (L_i/d = 2.5) for series A, B and C and 3.3 times the effective depth of the beam (L_i/d = 3.3) for series D.

In series A (f_{cm} = 31.1 MPa) a particular emphasis was given to the influence of the percentage (ρ_f) and orientation of the laminates (θ_f) on the shear strengthening of RC beams that have a certain percentage of steel stirrups. In fact, existing RC beams requiring shear strengthening intervention often have a certain percentage of steel stirrups. Three inclinations of laminates were tested (45°, 60° and 90°) and, for each inclination, three levels of the CFRP percentage (ρ_f = 0.06%; ρ_f = 0.09–0.10%; ρ_f = 0.13–0.16%)

Table 1
General information about the series of the tested RC beams.

Series	ρ_f (%)[b]	θ_f (°)			ρ_{sw} (%)[c]	f_{cm} (MPa)	L_i/d
A (ρ_{sl} = 2.9%)[a]	0.06	90	45	60	0.10 (ϕ6@300)[d]	31.1	2.5
	0.09–0.10						
	0.13–0.16						
B (ρ_{sl} = 2.8%)	0.07–0.08	90	45	60	0.10 (ϕ6@300)	39.7	2.5
	0.11–0.13						
	0.16–0.19						
	0.07–0.08				0.17 (ϕ6@180)		
	0.11–0.13						
C (ρ_{sl} = 2.8%)	0.07–0.08	90	45	60	0.10 (ϕ6@300)	18.6	2.5
	0.11–0.13						
	0.07–0.08	45		60	0.17 (ϕ6@180)		
	0.11–0.13						
D (ρ_{sl} = 3.1%)	0.07–0.08	90	45	60	0.10 (ϕ6@300)	59.4	3.3
	0.11–0.13						
	0.07–0.08	45		60	0.16 (ϕ6@200)		
	0.11–0.13						

[a] The percentage of the longitudinal tensile reinforcement was obtained from $\rho_{sl} = (A_{sl}/(b_w \times d)) \times 100$ where A_{sl} is the cross sectional area of the longitudinal tensile steel reinforcement (see Fig. 1), b_w = 180 mm is the width of the beam's web and d is the distance from extreme compression fiber to the centroid of tensile reinforcement.

[b] The CFRP percentage was obtained from $\rho_f = ((2 \times a_f \times b_f)/(b_w \times s_f \times \sin\theta_f)) \times 100$ where a_f and b_f are the dimensions of the laminate cross section.

[c] The percentage of the vertical steel stirrups was obtained from $\rho_{sw} = (A_{sw}/(b_w \times s_w)) \times 100$ where A_{sw} is the cross sectional of the arms of a steel stirrup, and s_w is the spacing of the stirrups.

[d] ϕ6@300 means steel stirrups of 6 mm diameter spaced at 300 mm in the shear span L_i.

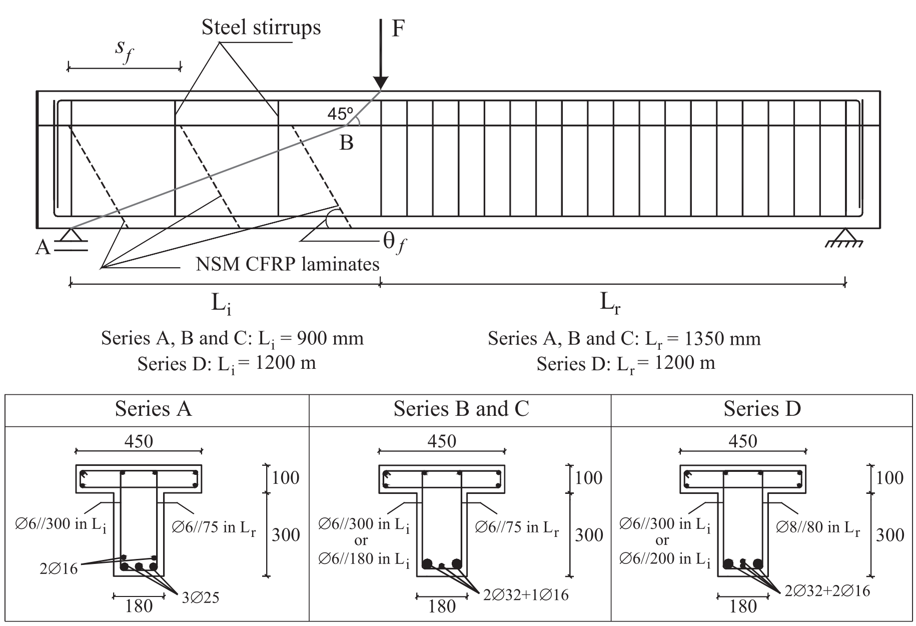

Fig. 1. General information about the tested RC beams (dimensions in mm).