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Shear tests of reinforced concrete beams with continuous rectangular spiral reinforcement

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HIGHLIGHTS

- Tests of shear-critical RC beams with rectangular spirals as shear reinforcement.
- Advanced continuous rectangular spiral with shear-favourably inclined vertical legs.
- The use of spiral reinforcement provided enhanced shear capacity and performance.
- Beams with advanced spirals showed highly improved post-peak deformation ductility.
- Predictions of maximum shear strength are presented and compared with test results.

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ABSTRACT

The behaviour of reinforced concrete shear-critical beams with rectangular cross-section and continuous rectangular spiral reinforcement as transverse reinforcement under monotonous loading is experimentally investigated. Further, an advanced rectangular spiral reinforcement that has shear-favourably inclined vertical links is also presented and tested as shear reinforcement. The experimental program includes eight (8) beams. Test results clearly indicate that the use of rectangular spiral reinforcement provided enhanced bearing capacity and improved shear performance in the examined beams. Beams with spiral reinforcement spacing at 120 mm and 80 mm exhibited 14.9% and 14.7% increased shear capacity with respect to the corresponding beams with stirrups, respectively. Furthermore beams with advanced spirals spacing at 120 mm and 80 mm exhibited 17.2% and 21.7% increased shear capacity with respect to the corresponding beams with stirrups, respectively. Moreover, the beams with advanced spirals exhibited deformation ductility values 2.10 and 2.60, respectively, demonstrating this way improved post-peak deformation ductility compared to the beams with equal quantity of commonly used stirrups.

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1. Introduction

It is generally recognised that the use of continuous spiral reinforcement in Reinforced Concrete (RC) elements with cyclic cross-section can substantially improve the strength and the ductility of the concrete and henceforth the overall seismic response and capacity of the structural element [1–3]. Recently, the use of continuous spiral reinforcement has been extended in RC elements with rectangular cross-sections. The extension of the use of rectangular continuous spiral reinforcement in elements with rectangular cross-sections is a new promising technology that is estimated it can enhance the capacity and the performance of these RC members [4].

It is emphasised that spiral reinforcement extends like an accordion and therefore it can positively and quickly be tied into place. This installation obviously reduces labour cost with respect to the installation of the single closed stirrups. Furthermore, common single closed stirrup installation demands the formation of two end hooks for anchorage. The length of these two hooks for each closed stirrup is an extra amount of the material that increases steel weigh and eventually the total cost. In spiral reinforcement installation this is not required and therefore, the total cost is obviously reduced. This benefit becomes substantial in the cases of RC columns where multiple stirrups per cross-section are required to be placed and further to the extra hooks, steel overlaps of stirrups are also unavoidable. Thus, reduction of the cost due to the nature of the application of the new product is yielded from the use of continuous spiral reinforcement and in some cases it may be considered as an important benefit.

RC beam-column joints, columns and infilled frames with rectangular members and rectangular spirals as shear reinforcement have already been tested under cyclic loading [4–8]. The experimental results of these tests revealed that the application of rectangular spiral reinforcement is at least equally effective as the common stirrups and in some cases spiral reinforcement has

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even improved the overall seismic performance of the examined specimens. Especially for the case of external beam-column joints, the use of spiral shear reinforcement in the joint area was found to be beneficial since the maximum loading, the energy absorption and the ductility capabilities of the spirally reinforced specimens were increased with respect to the corresponding conventionally reinforced joints with stirrups [6,8].

First results of the use of rectangular spiral reinforcement in shear-critical RC beams with rectangular cross-section have been reported by Karayannis et al. [9], whereas Yang et al. [10] examined the shear behaviour of concrete T-beams that have been reinforced using spiral-type wire rope as internal shear reinforcement.

Considering the behaviour of shear-critical members, it is stressed that the shear failure of a RC beam is characterised by the inclination of the diagonal cracking. It has been experimentally verified that the amount of the steel stirrups along with the amount of the main tension reinforcement and the span-to-depth ratio control the inclined shear cracking [11]. Potential cyclic load reversals due to seismic excitations may alter the angle of the diagonal shear cracking [12]. The replacement of steel stirrups with non-conventional reinforcement in shear-critical beams has also been investigated. The use of steel fibres as the only shear reinforcement in lieu of stirrups in concrete beams under predominant shear and torsion proved to be a promising alternative solution under specific circumstances [12,13]. The application of steel spiral reinforcement though seems to be a more effective technique. However, it is stressed that common continuous spiral reinforcement comprises two vertical links with opposite inclination and therefore, only one of these links has the right inclination to resist against the applied shear.

As it can be concluded from the review of literature most of the experimental research has been conducted to investigate the behaviour of spirally reinforced circular RC elements. So far, the published work on the use of rectangular spiral reinforcement as shear reinforcement in RC elements with rectangular cross-section is very limited, mainly carried out by the authors and therefore this area is still an open field of study.

In this work, the behaviour of RC shear-critical beams with rectangular cross-section and rectangular spiral reinforcement as transverse reinforcement under monotonous loading is experimentally investigated. Further, an advanced rectangular spiral reinforcement that consists of shear-favourably inclined vertical links is also presented and tested here as shear reinforcement for the shear-critical beams. The contribution of the examined rectangular spiral reinforcement to the capacity and to the overall performance of the tested beams is also reported and commented.

In this study, the analytical model of Zararis [11,14] and the design provisions of the Eurocode (EC2-04) [15] and the ACI Building Code (ACI 318-02) [16] have been used in order to estimate the ultimate shear strength of the tested beams. Based on the observed test results, a first approach to estimate the contribution of the spiral reinforcement on the ultimate shear capacity is also presented herein.

2. Experimental program

The experimental program of this research includes eight (8) beams with rectangular cross-section subjected to monotonic action of shear. Two beams have no shear reinforcement and they are used as control specimens. The transverse reinforcement of four specimens are continuous steel spirals with rectangular shape (rectangular spiral reinforcement), whereas two specimens have common closed stirrups.

2.1. Characteristics of the tested beams

All beams have the same dimensions as shown in Fig. 1. Their total length is 1840 mm, the shear span is $a = 720$ mm and the height to the width ratio is $h/b = 300/200$ mm. The specimens are sorted in three groups; Control specimens (2 beams without shear reinforcement), Group-120 (3 beams) and Group-80 (3 beams), as shown in Fig. 1. The span-to-depth ratio equals to $a/d = 2.67$ for all the beams of the experimental program except for control beam L2 where this ratio is $a/d = 2.77$.

The longitudinal reinforcement of the tested beams is four longitudinal bars of diameter 18 mm as tension reinforcement and two bars of 14 mm as compression reinforcement (2$\varnothing$14 top and 4$\varnothing$18 bottom). Only control specimen L2 has 3 bars of 18 mm as bottom reinforcement. The bottom and top bars of all specimens were hooked upwards and downwards respectively beyond the supports and enclosed by an extra steel stirrup at each end in order to preclude a potential anchorage slippage or even failure of the longitudinal reinforcement. The measured yield and the ultimate tensile strength of the tensional steel bars $\varnothing$18 were $f_{yl} = 550$ MPa and $f_{ul} = 690$ MPa, respectively. The flexural tension, ρ_l, and compression, ρ'_l, reinforcement ratio is calculated using the following expressions and summarised in Table 1:

$$\rho_l = \frac{A_{sl}}{bd} \quad \text{and} \quad \rho'_l = \frac{A'_{sl}}{bd} \tag{1}$$

where b and d are the width and the effective depth of the cross-section of the beam, respectively and A_{sl} and A'_{sl} are the area of the tension and the compression steel reinforcement, respectively.

Beams L1 and L2 of group Control have only longitudinal bars. No shear transverse reinforcement has been provided within the shear span of these beams.

Specimens of Group-120 and Group-80 are sorted based on the spacing of their transverse reinforcement; 120 mm and 80 mm, respectively. Each group consists of three beams; one with common closed stirrups, one with continuous rectangular spiral reinforcement (see also Fig. 2a) and one with rectangular spiral reinforcement which has shear-favourably inclined vertical links (see also Fig. 2b). Geometrical details and the links inclination of both rectangular spiral reinforcement types are also presented in Fig. 2. Mild steel stirrups and spirals have the same diameter of 5.5 mm ($\varnothing$5.5). The yield and the ultimate tensile strengths of the transverse steel reinforcement were measured $f_{yt} = 310$ MPa and $f_{ut} = 430$ MPa, respectively.

Table 1 also presents the values of the transverse reinforcement ratios, ρ_t and $\rho_{t,\varphi}$, of each beam based on the following relationships (2a) and (2b) for stirrups and spiral reinforcement, respectively:

$$\rho_t = \frac{A_{st}}{bs} \tag{2a}$$

$$\rho_{t\varphi} = \frac{A_{st}/2}{bs\sin\varphi_{front}} + \frac{A_{st}/2}{bs\sin\varphi_{back}} \tag{2b}$$

where $A_{st} = 2(\pi\phi_t^2/4)$ is the area of the two-legged stirrup or the two linked spiral reinforcement with diameter $\varnothing_t$, s is the uniform spacing of the shear reinforcement, φ_{front} and φ_{back} are the angles between the front and the back vertical link, respectively, of the spiral reinforcement and the beam axis perpendicular to the shear force.

The codified names of the beams presented in Figs. 1 and 2 and Table 1 comprise two parts of digits. The first part indicates the reinforcement: "L" for the control beams without shear reinforcement (with longitudinal bars only), "ST" for the beams with stirrups, "SP" for the beams with continuous spirals and "SPA" for the beams with advanced spirals which means spiral

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