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Confinement effect of different arrangements of transverse reinforcement on axially loaded concrete columns: An experimental study

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Abstract: Concrete behaves as a brittle material due to its low inherent tensile strength, but it can also exhibit a markedly ductile behavior when coupled with transverse reinforcement like steel stirrups. The role of stirrups is to enhance confinement effect, to restrain the lateral expansion of concrete, thus modifying the concrete stress-strain constitutive law and enabling higher compression strains and higher ductility. This paper focuses on the confinement effect induced by different arrangements of transverse reinforcement on axially loaded concrete columns. An experimental campaign has been carried out, comprising 18 concrete columns with two different mechanical strengths and reinforced with three different layouts of stirrups, namely typical closed square hoops, closed stirrups with additional cross ties, and a novel type of stirrups involving rectangular hoops with additional restraint plates, the latter offering an enhanced diffused confinement action and limiting extensive spalling of the cover concrete. Formation and propagation of longitudinal micro-cracks are reduced with the novel type of diffused stirrups and a moderate-to-high increase of ductility is observed. However, the beneficial effects induced by diffused stirrups are more pronounced in medium-strength concrete and almost negligible in low-strength concrete that collapses due to a brittle cracking failure without involving the confinement action of the transverse reinforcement.

Keywords: Concrete; Steel stirrups; Transverse reinforcement; Ductility; Confinement; Microcracks

1 Introduction

The concept of capacity design in structures is becoming increasingly important: the goal is to ensure that plastic deformation occurs in specified zones that have a markedly ductile behavior so as to avoid brittle failure mechanisms and promote an overall ductile global collapse mechanism of the structure. In order to meet this requirement, the materials the structure is made of should be able to undergo large plastic deformations without failure. This concept is incorporated in technical regulations and standards in force in many countries like Italy, Europe, New Zealand, America [1–4].

Of particular relevance to the present paper, ductility and plastic deformations occurring in concrete structures should be guaranteed up to certain load levels well beyond the elastic limit load. In this regard, *unconfined* concrete has a mainly brittle behavior: when subject to compression loads, high lateral strains arise due to formation and propagation of microcracks. This, in turn, implies that instability in the compression zone as well as instability of the compressed longitudinal steel bars may occur. All these circumstances make the plain (unconfined) concrete a material that is less suitable for complying with the capacity design principles. On the contrary, transverse reinforcement, e.g. steel stirrups, limits the lateral expansion of *confined* concrete, which can thus sustain higher compression strains before failure takes place. As a result, confined concrete exhibits higher ductility and a markedly different stress-strain constitutive law in comparison with unconfined concrete. Reinforcement bars and stirrups mitigate many complex post-elastic phenomena exhibited by plain concrete at incipient failure, such as localization, cracking, fracturing/damaging mechanisms, see in this context Bažant [5] and references therein. In the relevant literature, this physical circumstance has justified the use of plasticity-based approaches for modelling the mechanical behavior of confined concrete [6], and the use of limit analysis theory for the determination of the load-bearing capacity of concrete structural elements and structures, see

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e.g. Bræstrup et al. [7], Nielsen and Hoang [8], and the recent papers by Limam et al. [9, 10], Larsen et al. [11], Pisano et al. [12–15], and De Domenico et al. [16–19].

Typical confinement on concrete is exerted by steel spirals or circular hoops that, when concrete expands under axial loads, provide restraint and effectively contrast this expansion. Other commonly used layouts of transverse reinforcement involve square or rectangular hoops, which may be further enhanced by placing additional cross-ties (or overlapping hoops). The latter play a key role in limiting the spacing between subsequent transverse sets, thus making the effectively confined concrete area larger.

Many papers in the literature explored the confinement effects induced by stirrups on axially loaded concrete. Pioneering work was carried out in the late 80s by Mander et al. [20], [21], who developed a popular analytical model to describe the stress-strain behavior of confined concrete and proposed the concept of "effectively confined area" that has been incorporated in design guidelines and technical standards afterwards. The Mander et al. model was validated on an experimental basis through the results of 31 reinforced concrete columns under axial load and with a variety of arrangements of transverse reinforcement (spiral reinforcement, square and octagonal transverse hoops, rectangular hoops). Another analytical model to predict the stress-strain law of normal and high-strength concrete columns confined with spirals was elaborated some years later by El-Dash and Ahmad [22]. On the basis of the "equivalent uniform confinement pressure", Razvi and Saatcioglu [23] developed a confinement model applicable to high-strength concrete, for which many formulations proposed for normal-strength concrete turn out to be inaccurate. Binici [24] proposed an analytical model to describe the strength and ductility of confined concrete based on the Leon-Pramono failure criterion. Braga et al. [25] performed an analytical study to determine the confining pressures of transverse reinforcement on the concrete core. Experimental investigation on the confinement action exerted by transverse reinforcement on high-strength short concrete columns was performed by Campione and Minafò [26] and by Campione [27]. Faleschini et al. [28] performed an experimental investigation on the determination of strength and ductility of beam-column joints made of electric-arc-furnace concrete under cycling loading. They investigated energy dissipation and ductility and linked these properties to the material properties and to the stirrups layouts adopted. Castaldo et al. [29] carried out numerical simulations to predict the strength, post-elastic behavior and ductility of different structural members like walls, deep beams, and panels, in the framework of a nonlinear finite element analysis.

Along this research line, the present paper aims to investigate the confinement effect of different arrangements of transverse reinforcement on axially loaded concrete columns. To this end, an experimental campaign has been carried out, comprising two types of concrete strengths, three different arrangements of transverse reinforcement, and an overall number of 18 axially loaded concrete columns. Besides ordinary (conventional) square hoops and configurations of closed stirrups with additional cross ties, a novel type of stirrups involving rectangular hoops with additional restraint plates has been designed and used in the experimental tests. This scheme, which represents the main novelty of the present experimental study, has its foundation in the "effectively confined area" concept proposed by Mander et al. [20]. In fact, this novel reinforcement scheme allows maximizing the effectively confined core by widening the reacting zone associated with the transverse reinforcement, passing from the simple cross-section of the steel bar to the broader surface covered by the restraint plate, thus ensuring a diffused confinement action. The experimental stress-strain relationships for the various reinforcement arrangements have been evaluated experimentally and then critically examined in order to identify and scrutinize ultimate compression strain and resulting ductility for all the tested concrete columns in a comparative manner.

2 Preliminary remarks on confined concrete

By observing the simple sketch of Figure 1, it is clear that confined concrete behaves as a two-phase material when subject to axial load: one phase is that related to the area inside the stirrups, which is the effectively confined core, and another phase is represented by the concrete cover outside the perimeter of the stirrups, with no confinement. While tested in compression, the stirrups prevent the internal concrete core from expanding laterally. This concept is well known and dates back to the work of Mander et al. [20, 21] of the late 80s.

To maximize the effectively confined concrete core one could reduce the stirrups spacing along the height of the column (cf. right part of Figure 1) or introduce additional cross ties to limit the free span of the stirrups in the plan view (cf. left part of Figure 1). Building on this concept, a novel type of transverse reinforcement has been designed that is able to extend the effectiveness of the confinement

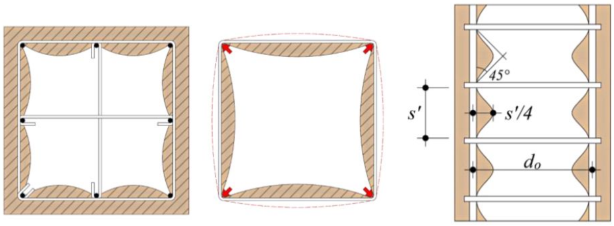

Figure 1: Sketches of the “effectively confined core” concept on square concrete column elements

action exerted by the stirrups over a broader area. The motivation of this novel reinforcement scheme is to obtain an enhanced diffused confinement action in order to limit spalling of the cover concrete under axial load.

3 Experimental campaign

3.1 Specimen preparation and reinforcement arrangements

The experimental campaign has comprised 18 concrete columns tested up to failure under axial load. Two different batches of concrete have been employed in this study, using an ordinary Portland cement with aggregates: nine columns have been prepared with a *low-strength* concrete (compressive strength of around 10 MPa) and the remaining nine columns with a medium-strength concrete (compressive strength of around 30 MPa). As to the column dimensions, all the tested columns have square cross-section 25 x 25 cm and height of 40 cm.

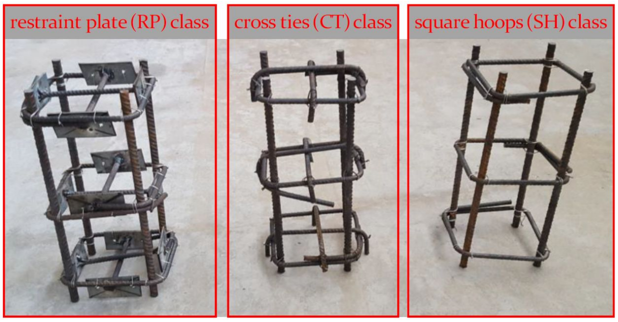

Figure 2: Different arrangements of transverse reinforcement considered in this experimental campaign: RP class (left), CT class (center), SH class (right)

The focus of this experimental investigation is on the confinement action exerted by different arrangements of transverse reinforcement. In particular, for each class of concrete strength (i.e., each group of nine columns), three columns have been reinforced with ordinary (conventional) square hoops (SH class), three columns have been reinforced through closed stirrups with additional cross ties (CT class) and finally the remaining three columns have been reinforced with a novel type of stirrups involving rectangular hoops with additional restraint plates (RP class). The latter arrangement of transverse reinforcement represents a novel reinforcement scheme and is the main novelty of the present experimental investigation. The three schemes of reinforcement are illustrated in the photograph shown in Figure 2. Some close-up details of the novel RP scheme are provided in Figure 3 – as can be seen, the RP scheme maximizes the effectively confined concrete core due to the presence of the restraint plates.

With regard to the parameters underlying the design of such novel RP transverse reinforcement scheme in case of columns of real dimensions, the following preliminary criteria can be adopted: 1) the thickness of the plate should be designed based on the lateral expansion of concrete when subject to an axial load corresponding to its ultimate compression capacity, assuming a Poisson’s ratio equal to 0.2; 2) the extension of the plates along the sides should be chosen in proportion with the column lateral dimensions, the actual stirrups spacing and on the basis of a target amount of ductility. In the present study, the restraint plates have dimensions 4 x 8 cm and thickness 3 mm, while the linking cross-tie is a steel bar with 8 mm diameter.

As to the reinforcement bars (re-bars), the longitudinal reinforcement of the concrete columns is constituted by four B450C steel bars of 10 mm diameter placed at the four corners of the cross-section, with 2.5 cm concrete cover. Transverse re-bars are also made of B450C steel for all the analyzed specimens, have 8 mm diameter and a constant spacing of 13 cm along the height of the column. Some photographs regarding the final stirrups configurations for the 18 specimens are reported in Figure 4, while the specimen preparation relevant to a single concrete batch (9 specimens) is illustrated in Figure 5.

3.2 Testing conditions

The compressive strength of the concrete used has been determined through compression tests on cube specimens of 15 cm side cured in water for 28 days, cf. Figure 6. The compressive tests have been performed in accordance with UNI EN 12390-4, with a load rate of 50 N/cm^2 until failure, using a CONTROLS test frame model 65-L1301/FR

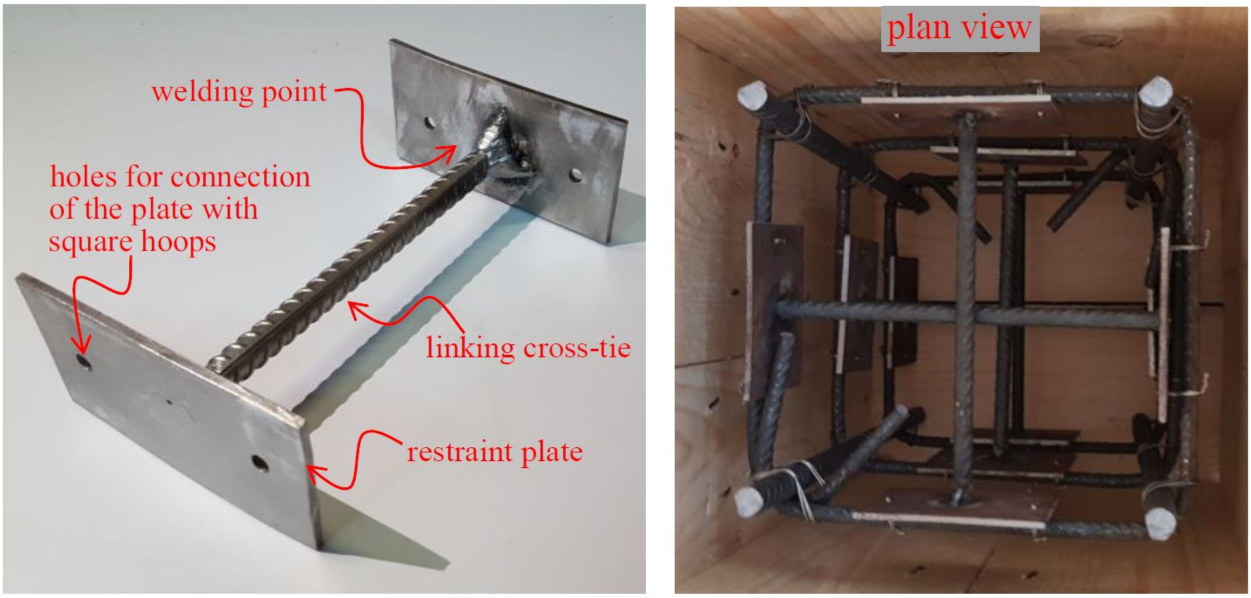

Figure 3: Close-up details of the novel RP transverse reinforcement scheme

with 250 kN load capacity [30]. The values of the compressive strengths obtained for 6 low-strength concrete specimens ranged from 9.8 MPa to 11.4 MPa, with an average of 10.4 MPa, whereas the compressive strength values for the medium-strength concrete cubes ranged from 27.0 MPa to 32.0 MPa, with an average of 30.3 MPa.

Additional tests have been carried out to determine the Young's modulus of concrete. Concrete cylinders of 95 mm diameter and 190 mm height have been tested in accordance with UNI 6556. The Young's modulus is equal to 21 GPa for the low-strength concrete (only one cylinder has been tested), and ranging from 26.25 GPa to 34.71 GPa for medium-strength concrete (9 cylinders have been tested), with an average of 29.58 GPa. These values are in good agreement with the compressive strengths for the two classes of concrete batches.

The 18 concrete columns with different reinforcement arrangements (labelled SH#, with # the number of specimen equal to 1,2,3) have been tested in compression until failure. A servo-hydraulic MATEST testing equipment model C088PN104/AD/0001 with 4000 kN load-carrying capacity has been used, with load rate of 0.5 MPa/s. The testing equipment has been instructed so as to conclude the test if the recorded load attains a decrease of 20% in comparison with the peak load value. The column is equipped with three strain gauges on three distinct faces of the specimens to record the axial strain, while a LVDT has been mounted on the upper plate to control the displacement during the test. The actual strain of the column is calculated as the mean of the three strain gauge measures; as soon as one or two of these strain gauges detach from the concrete face, the corresponding measure is ignored in the calculated of the mean.

4 Experimental results

The stress-strain curves of the 18 reinforced concrete columns are not reported for the sake of brevity. With regard to the specific measurements, it is worth pointing out the following experimental observations: for low-strength concrete, all the 9 specimens failed in a consistent manner, and the test was successfully carried out; for the SH1 specimen of the medium-strength concrete columns, the axial strain recording was affected by a premature detachment of two strain gauges, and only one strain gauge, partially detached, was considered (this measure is, in fact, considerably larger than the other two specimens of the same class, SH2 and SH3); the RP2 specimen of the medium-strength concrete columns failed prematurely, probably due to some defect in the preparation of the sample. Considering these observations, the mean stress-strain curve of the three classes of transverse reinforcement for the medium-strength concrete columns is reported in Figure 9, whereas the most important values for the low-strength concrete columns are reported in Table 1.

It can be seen that the novel RP configuration of transverse reinforcement effectively increases the maximum axial strain in the medium-strength concrete columns (with a mean increase of around 140% – cf. the mean curves in Fig-

Table 1: Mean values of the most important values of the stress-strain curves for the low-strength concrete columns

reinforcement arrangement	peak compressive stress	axial strain at peak stress	maximum axial strain
	f_{cc} [MPa]	ε_{cc} [–]	$\varepsilon_{\max}$ [–]
Square hoops (SH)	8.91	0.0052	0.0084
Cross ties (CT)	7.95	0.0053	0.0074
Restraint plate (RP)	9.13	0.0046	0.0066

Figure 4: Stirrups configuration for the 9 low-strength concrete columns (top) and for the 9 medium-strength concrete columns (bottom)

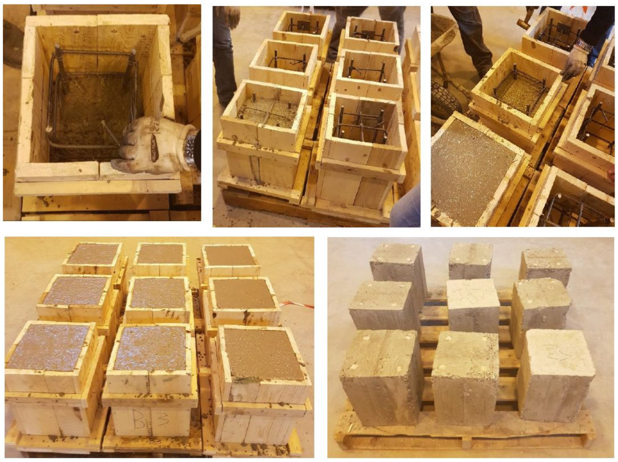

Figure 5: Specimen preparation phases, in chronological order from top left to bottom right, of concrete columns with different arrangements of transverse reinforcement

ure 9). The cross ties offer a modest enhancement of ductility of the columns as compared to the conventional (ordinary) square hoops configuration, and an increase in the strength. However, the above conclusions are only valid for the medium-strength concrete columns: in fact, by inspection of Table 1 it is seen that the trend for the low-strength concrete columns is quite different. In particular, passing from the SH to the CT and RP configurations there is a decrease, rather than an increase, of the maximum axial strain. This is ascribed to the class of concrete used in this specimens: indeed, the columns fail prematurely, before an effective mechanism of stress transfer occurs from the concrete core to the steel stirrups. While the peak compressive stress is increased in the RP case, the main goal of this enhanced reinforcement scheme is to increase the ductility, rather than the strength, of the concrete members. This enhancement of ductility is, however, achieved for medium-strength concrete, with an excellent increase of 140% of the maximum axial strain value. Furthermore, the formation and propagation of longitudinal micro-cracks are reduced with the novel type of diffused stirrups (RP class) as can be observed in the photographs reported in Figure 10. This is in line with the concepts stated in Section 2 and with the motivations for introducing the novel type of transverse reinforcement scheme.

5 Concluding remarks

This paper has presented an experimental investigation on the confinement effect exerted by different types of transverse reinforcement on axially loaded concrete columns. Besides the ordinary square hoops and the square hoops with additional cross ties, a novel type of reinforcement has been proposed, motivated by the effectively confined

Figure 6: Compression test in accordance with UNI EN 12390-4 on concrete cube sample

Figure 7: Determination of Young's modulus in accordance with UNI 6556 on concrete cylinders

Figure 8: Compression test on sample of reinforced concrete column: placement of strain gauges (left) and typical failure mode (right)

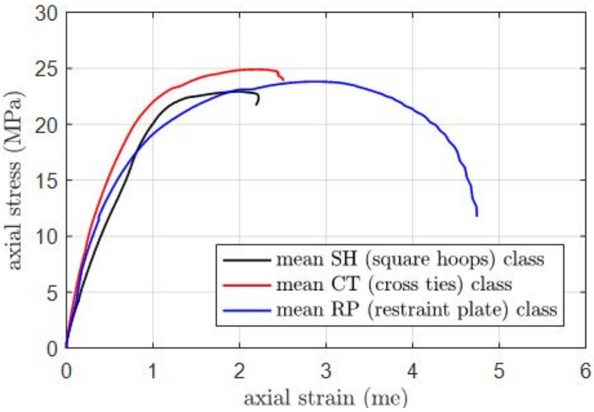

Figure 9: Mean stress-strain curves for medium-strength concrete columns with different arrangements of transverse reinforcement

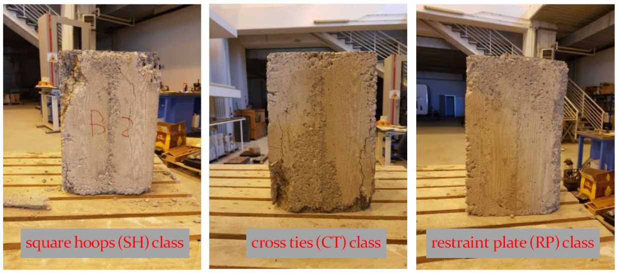

Figure 10: Typical crack patterns at failure of the medium-strength concrete columns with different arrangements of transverse reinforcement

concrete core concept introduced by Mander et al. [20]. This novel reinforcement scheme is based on squared hoops with additional cross ties that support some restraint plates, the latter being able to offer a diffused confinement action over a broader influence area. It has been demonstrated that this novel scheme of transverse reinforcement is very effective in increasing the ductility of the concrete columns: the mean value of the maximum axial strain at collapse has been increased of around 140% in comparison with the conventional (ordinary) square hoops scheme. However, having analyzed two different classes of concrete (in terms of their strength) has made it possible to highlight another important aspect regarding this novel reinforcement scheme: introducing this enhanced transverse reinforcement in low-strength concrete members may be useless, because the rupture may occur prematurely before any stress transfer mechanism takes place to engage the steel stirrups in their confinement action.

In conclusion, this experimental study has shed light on the effective capabilities of the novel reinforcement scheme for medium-strength concrete, which has been validated through experimental tests on small-scale reinforced concrete columns. Application of this novel reinforcement scheme to more realistic structural elements, for instance real-scale concrete beams and columns, as well as beam-column joints under cyclic loading, is the object of an ongoing research work.

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