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Seismic Behavior of Concrete Columns and Beams Reinforced with Interlocking Spirals

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Abstract— Columns of a rectangular cross-section with interlocking spirals are the latest development in bridge-building, where they are applied on piers of high earthquake-resistance requirements. This method can be applied also on soft stories of buildings, like pilotis. Flexural behavior of structural elements with interlocking spirals, but mainly their behavior due to shear, must be further investigated, both analytically and experimentally. This study refers to these problems, comprising an experimental and an analytical part. More precisely in the experimental part, the response of columns and beams with interlocking spirals is compared to the response of conventionally reinforced ones. Useful conclusions are drawn on the performance of these structural elements with the proposed reinforcement arrangement.

Index Terms— Columns, confinement, interlocking, piers, reinforced concrete, seismic, spirals

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1 INTRODUCTION

JUST like a circular column section, on account of architectural, construction (paper made formwork), seismic-resistance, etc. requirements, can be preferred to a square one, in the same way a rectangular section with two interlocking or non-interlocking spirals can be used instead of a corresponding conventionally reinforced one (Figs. 1a, 1b, 1c). This figure also shows the advantage of case (b) over case (a), in the case that seismic-resistance is required only in one principal direction of the section (economy, higher confining efficiency).

Rectangular columns with two interlocking spirals were for the first time proposed (and preferred to the conventional ones at that), by the competent U.S. Authority, the California Department of Transportation, for piers of earthquake-resistant bridges [4]. Few scientists throughout the world have conducted research on the behavior of structural components reinforced using interlocking spirals [7], [8], [9], [10], [11], [12], [13].

The authors of this study are convinced, that sections with interlocking spirals can perform just as well on critical stories, like pilotis of buildings, where concrete confinement requirements are especially high, due to low values of L/h (L: Column net height, h: Column section height), which as a rule imply failure due to shear.

The following two reasons are the main reasons for this preference:

1. Increased ductility as a result of the higher confining efficiency in circular column sections compared to rectangular ones and
2. Construction preferences, which nowadays favor the circular column sections, after replacement of traditional wooden formwork by throwaway type paper made ones, which can only be applied on circular cross-sections.

The second advantage can include also the feasibility of standardization, favoring mainly spiral reinforcement. This kind of spiral reinforcement, produced at various diameters, can, in the opinion of the authors of this study, constitute the standardized solution to a problem, solved until today following an especially arduous solution. All the more with the standardized solution, it is possible to make good use of higher class reinforcing steel for spirals, which is more effective than steel classes, used nowadays, as a rule.

It is noteworthy that despite the most encouraging experimental and analytical results of work by Tanaka and Park [5], [6], the research on the influence of the problem variables on the behavior of column sections with interlocking spirals, still remains almost stagnant. Cyclic shear (i.e. seismic type loading) is of particular importance from a research standpoint in connection with small shear span length elements.

Up to now, the problem of secure interlock of spirals has been sufficiently researched and a corresponding criterion has been formulated (Fig. 2). In accordance with the criterion in question, the interlock is secure on condition that the distance between centers of the interlocking spirals is not greater than 1.2 times the spiral radius r.

It is also recommended, once more, for the purpose of ensuring the interlock of spirals, that at least four longitudinal bars should be provided inside the interlocking area of the spirals (Fig. 3). It was ascertained that the presence of these longitudinal reinforcement improves the ability of the truss mechanism to carry shear forces.

As known, in the case of a simple circular section the expression giving the shear portion carried by the reinforcement, improved by Priestley [3] is:

$$V_s=\frac{\pi}{4}\cdot\left(2\cdot A_s\cdot f_{ys}\right)\cdot\frac{b}{s} \tag{1}$$

where

A_s is the section area of spiral bar
f_{ys} is the yield strength of the spiral steel
s is the centre to centre spacing of spirals
b is taken as equal to the diameter of cross section core.

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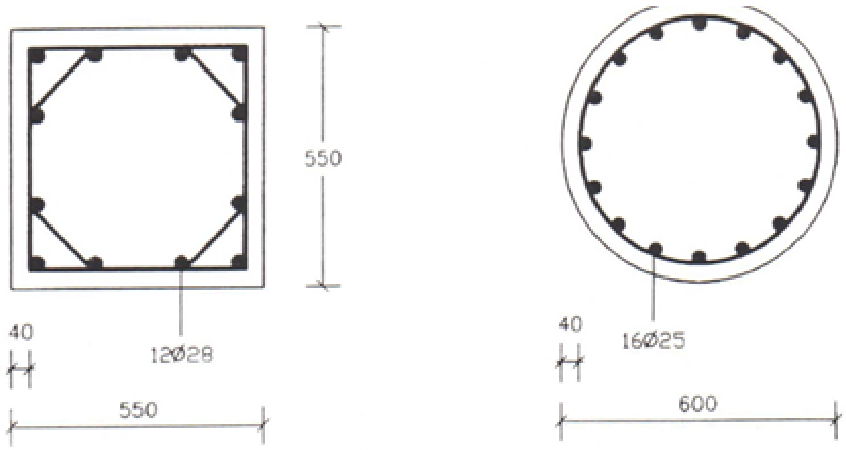
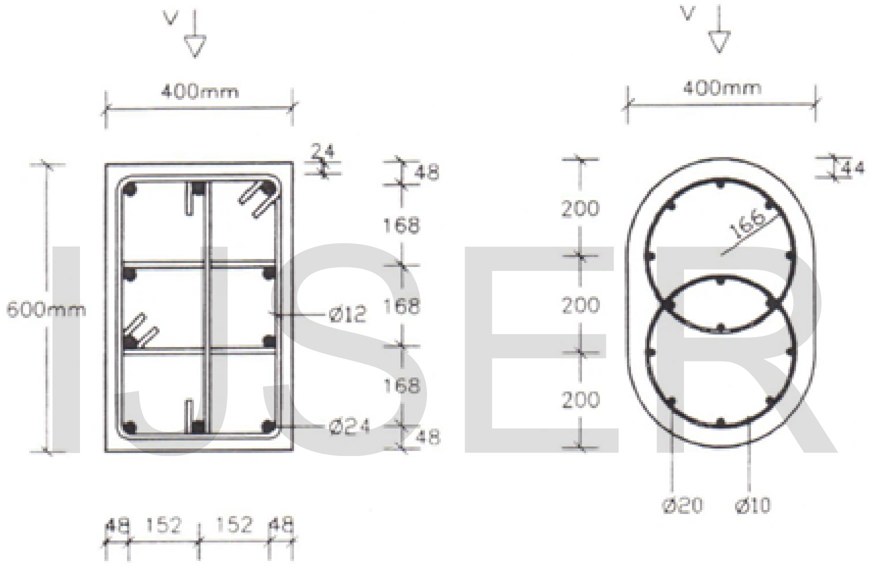
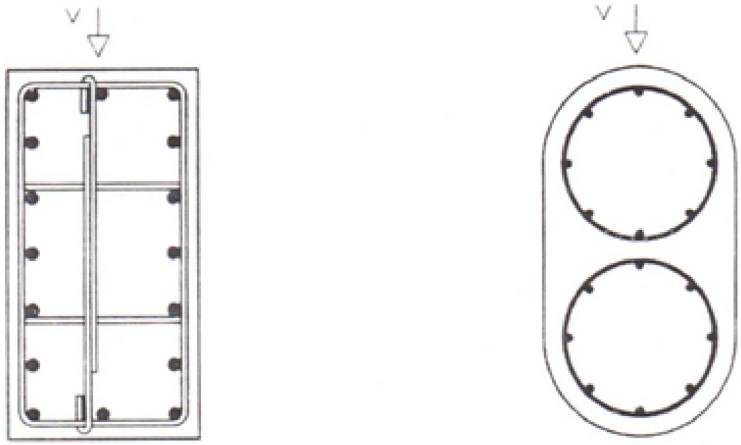


(a) Single



(b) Complex sections with interlock of transverse reinforcement



(c) Complex sections with reinforcement non interlocked

Fig. 1 Types of sections: (a) Single section, (b) Complex-section with transverse reinforcement, interlocked and (c) Complex sections with transverse reinforcement, non interlocked.

It is pointed out that ACI-318 standards [1], as well as NZS:3101 [2], use for the same quantity the familiar relation of the classical truss model:

$$V_s = \frac{2A_s}{s}\cdot z\cdot f_{ys} \tag{2}$$

where
z is taken as 0.8D, and
D is the diameter of the gross area of cross-section

Although Tanaka and Park [5], [6] propose the equation mentioned below for the shear carried by spirals with adequate interlock:

$$V_s = \frac{\pi}{4}\cdot\left(2\cdot A_s\cdot f_{ys}\right)\cdot\frac{D}{s} + 2\cdot A_s\cdot f_{ys}\cdot\frac{d}{s} \tag{3}$$

where
d is the distance between centers of interlocking spirals (Fig. 2)

The concept of an enveloping perimeter of a substitute section is introduced in the present study, attempting to correlate the bending resistance and shear resistance of the complex section considered with the bending and shear resistance of the sections with an enveloping perimeter proposed (Fig. 4).

More concretely, in order to obtain an (approximate) calculation of the ultimate moment resistance of the section with interlocking spirals, a circular enveloping perimeter for the substitute section is proposed with the same reinforcement (Fig. 4b), until the precise diagrams are completed which, in this phase, have not been fully elaborated. Whereas for estimating the section's resistance to shear and bending, an enveloping rectangle is proposed as perimeter of the substitute section (Fig. 4c). Now, as far as the amount of shear carried by the concrete is concerned, the familiar EC2 form of expression for rectangular cross-sections is proposed:

$$V_c = \left[\tau_{Rd}\cdot k\cdot\left(1.2+40\cdot\rho\right)+0.15\cdot\frac{N}{A_c}\right]\cdot b_w\cdot d \tag{4}$$

where
b_w the width of the rectangular substitute section
ρ half of the percentage of the longitudinal reinforcement of the section

Whereas for the shear portion carried by the reinforcement, expression (2) applies with z=0.8h, where h equals the depth of the rectangular substitute cross-section.

Naturally, in the case considered of complex sections with interlocking spirals, for the calculation of ρ, only the longitudinal reinforcement of one side (spiral) must be considered, as related to the whole rectangular cross-section.

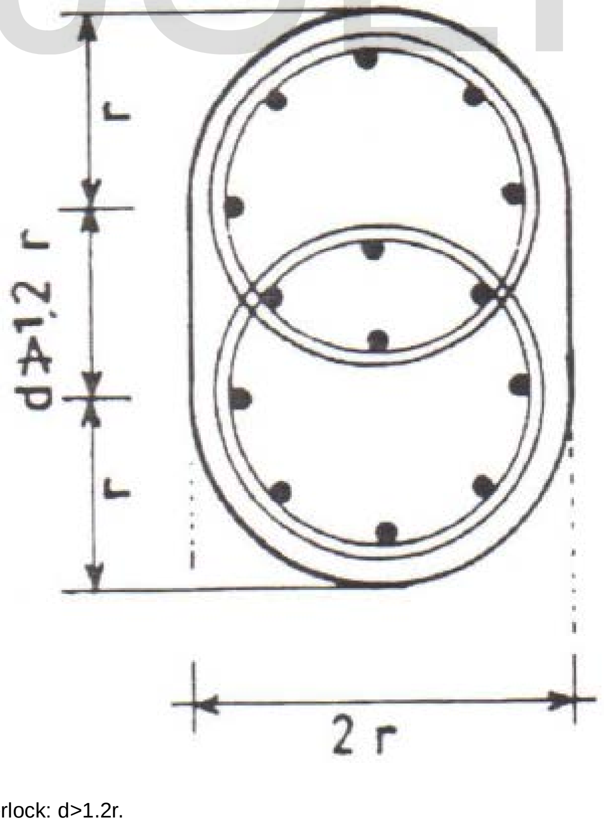


Fig. 2 Condition for secure interlock: d>1.2r.

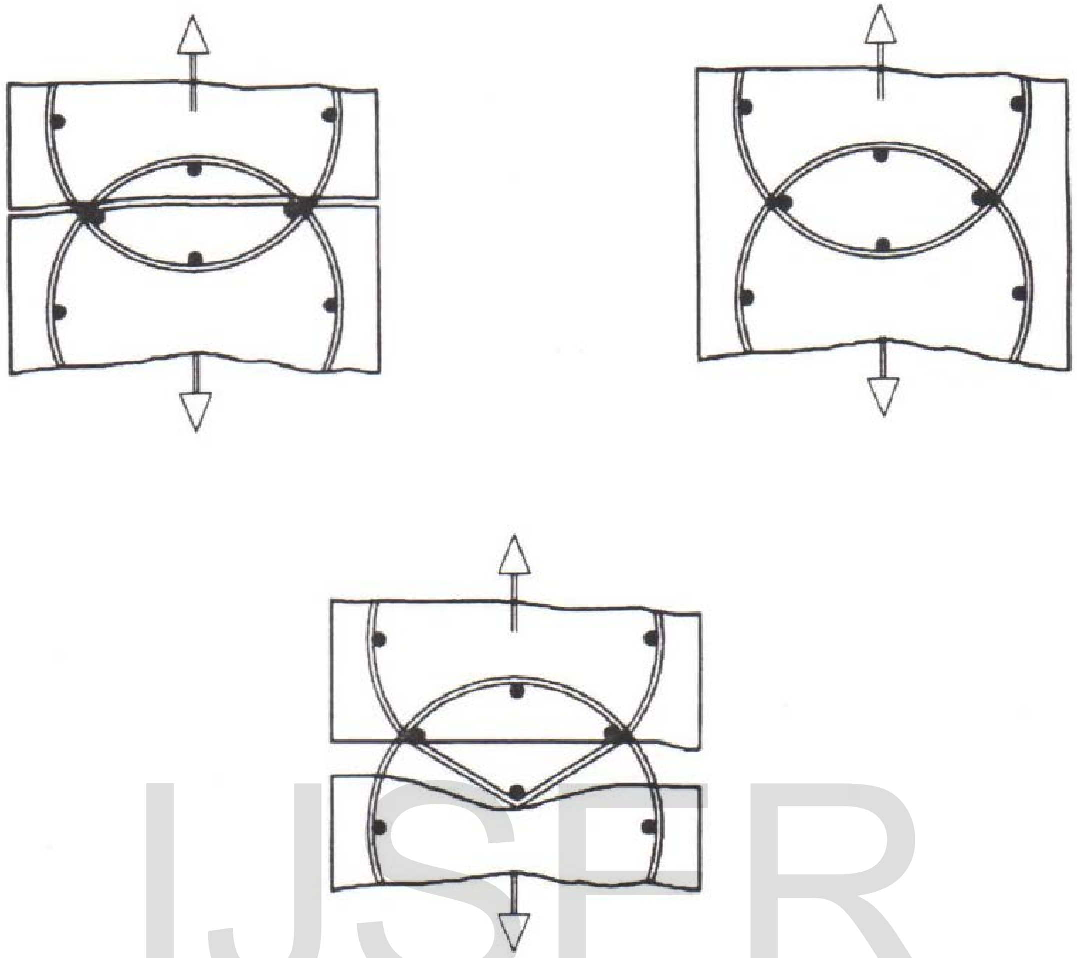


Fig. 3 Deformation of interlocking spirals due to diagonal shear cracking.

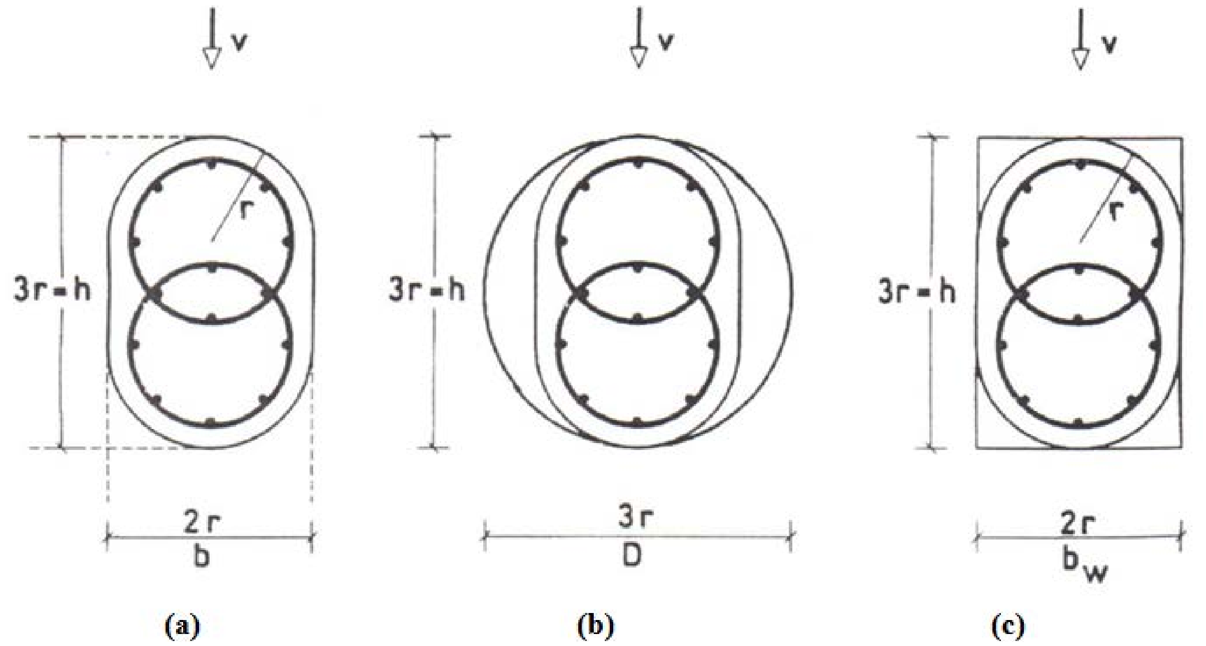


Fig. 4 Proposed sections with enveloping perimeter for an approximate design of complex sections: (a) Cross-section to be designed, (b) Enveloping circle for flexural analysis and (c) Enveloping rectangular for shear analysis.

2 RESEARCH SIGNIFICANCE

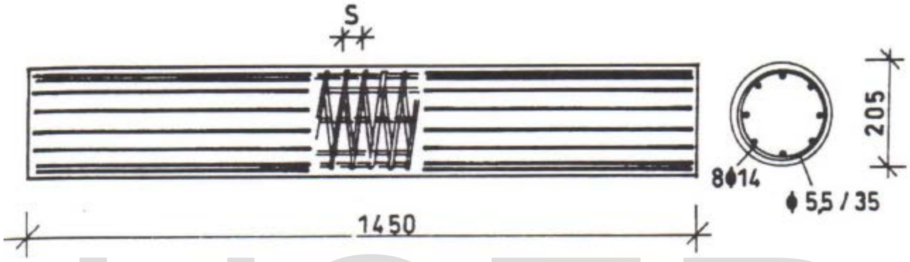
Laboratory of Reinforced Concrete and Masonry Structures has set out on an experimental but also analytical research into upgrading spiral reinforcement in column sections with varying ratios of section sides. The program includes 21 specimens under monotonic or cyclic loading, whereby the possibilities of improving the seismic resistance mechanical properties of elements with interlocking spirals or with spirals farther apart from each other will be investigated.

The second scope of the research, in addition to improving mechanical properties (strength, stiffness, ductility, energy dissipation capacity), is the constructional standardization of vertical elements in bridge construction through the utilization of spiral reinforcement.

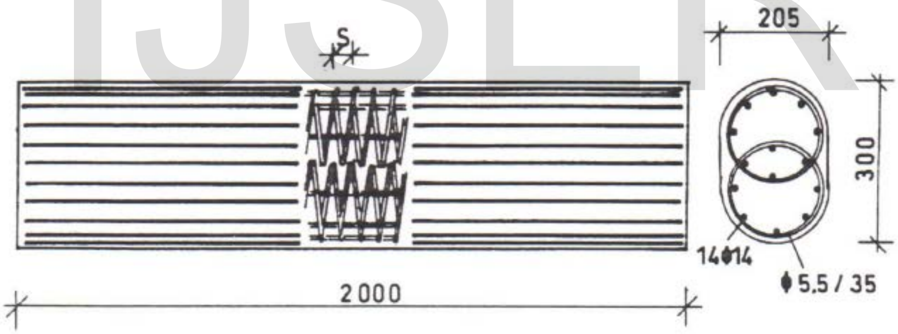
3 SPECIMENS

Three pieces of "pilot" specimen work were constructed, within the overall research framework, among which two with interlocking spirals and a third one with one plain spiral reinforcement used for comparison purposes with the preceding ones. Cross-sections and geometry of the specimens are shown in Fig. 5 while details concerning concrete, reinforcement, material properties and axial loading are summarized in Table 1.

Specimen 1



Specimen 2



Specimen 3

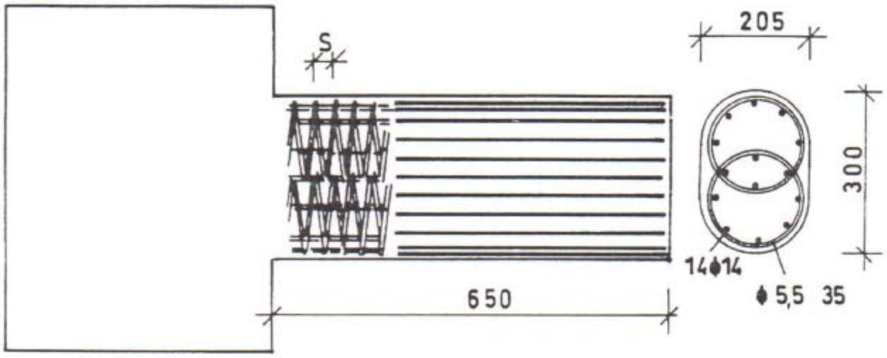


Fig. 5 Geometrical characteristics of specimens.

TABLE 1

MECHANICAL PROPERTIES OF SPECIMENS

Specimen	Normalised axial load	fc (MPa)	Longitudinal reinforcement		Spiral reinforcement		
			Ø (mm)	fy (MPa)	Ø (mm)	s (mm)	fys (MPa)
1	-	26.0	14	540	5.5	35	465
2	-	24.0	14	485	5.5	35	465
3	0.10	22.5	10	480	5.5	35	465

4 TEST SETUP AND INSTRUMENTATION

Test specimens 1 and 2 were subjected to monotonic loading as simply supported beams (Figs. 6, 7). Shear span-to-depth ratios were 3.5 for specimen 1 and 3.0 for specimen 2. Specimen 3 with span-to-depth ratio 2.0 was subjected to cyclic lateral loading (Fig. 8).

Specifically for specimen 3, cyclic lateral loading was applied using two one-way actuators and was measured using two load cells attached to the specimen. The data of the load cells were recorded through a digital Wheatstone bridge with great precision.

The point load displacements δ of the cantilever-specimen were measured through a specific potentiometer onto an electronic voltmeter and the control of the actuator displacements was carried out by linear variable differential transducers (LVDT) attached to the actuator caps and connected to the controller.

Finally, the axial load was imposed on specimen 3 by a hydraulic compression jack, mounted on moveable cart which could be laterally displaced together with the laterally loaded free end of the specimen.

Fig. 6 Loading of specimen 1.

Fig. 7 Loading of specimen 2.

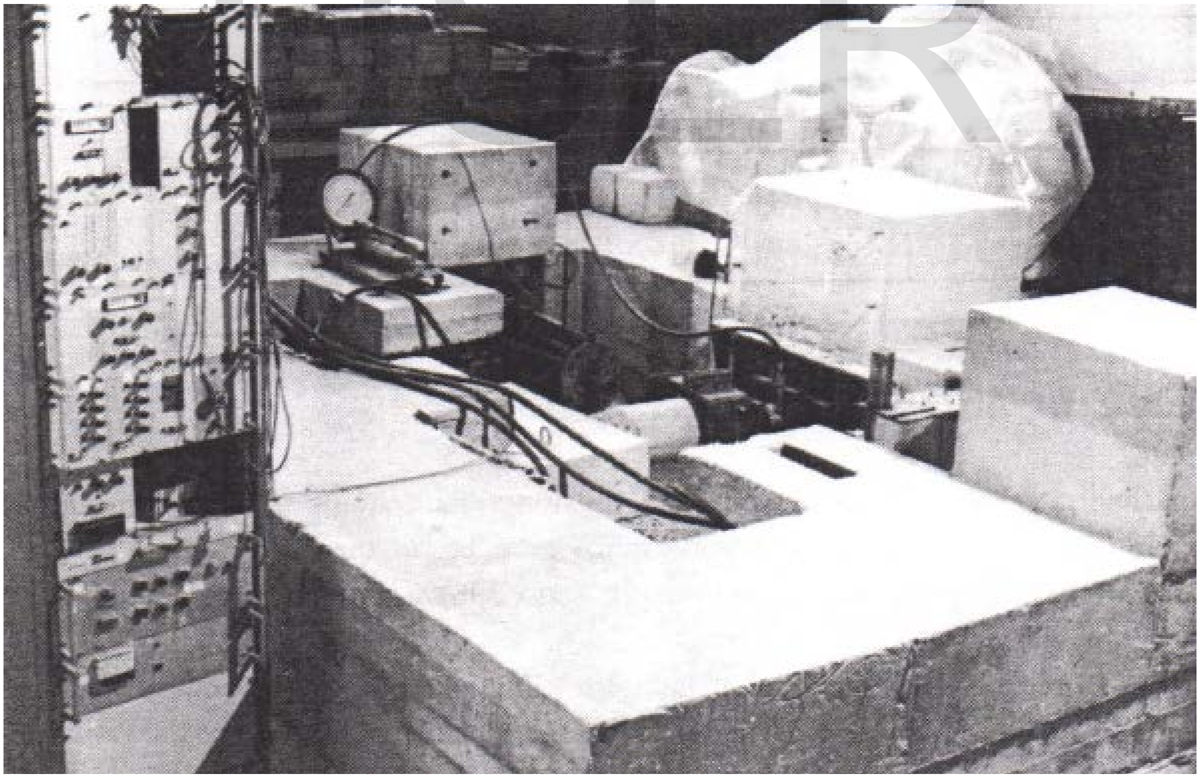


Fig. 8 Loading of specimen 3.

5 EXPERIMENTAL RESULTS

5.1 Specimens 1 and 2

For specimens 1 and 2, the progressively-increasing loading was recorded, and the ultimate load carried was noted (Figs. 6, 7). In both cases, flexural-shear cracks appeared on either side of the point load with a minimum 45° degree inclination.

This typical crack pattern was succeeded by a typical shear cracking at a 45° degree inclination towards the support points around the element axis.

Finally, in the support areas of the element and at a latter stage of loading, near the ultimate load-carrying capacity, the characteristic tied arch mechanism cracks appeared with bigger inclination. It is noteworthy that also in the case of specimen 2 with the complex cross-section, a uniform cracking-configuration was observed without any signs of separation of the interlocking spirals at any point of the span length under the ultimate load-carrying capacity. It was expected that a critical spiral disconnection area would come up near the supports due to maximum shear (Fig. 9). According to Fig. 9, the alteration of forces in the tension zone causes shear at the level of overlapping spirals of the complex cross-section equal to the shear on the same point of the beam.

Finally, specimen 1 failed showing, almost at the same time, symptoms of ultimate resistance due to bending and shear. The capacity value recorded was 220 kN. Failure of specimen 2 took place in the same manner and the capacity value measured was 350 kN.

Fig. 10 shows some calculation curves which give, for various values of the mechanical volumetric ratio of transverse steel ω, the normalized moment μ. The same figure also indicates the values pertaining to: a) the experimental results of the three specimens, b) the values calculated on the basis of the proposed substitute cross-sections with an enveloping perimeter (Fig. 4).

The real strength (resulting from the tests) of specimens with interlocking spirals is equal to 80% of the strength calculated on the basis of specimens with the substitute cyclical cross-section (Fig. 4b).

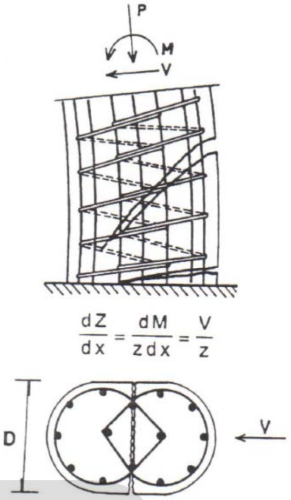


Fig. 9 Stress inside the interlock area is proportional to the existing shear of the cross section.

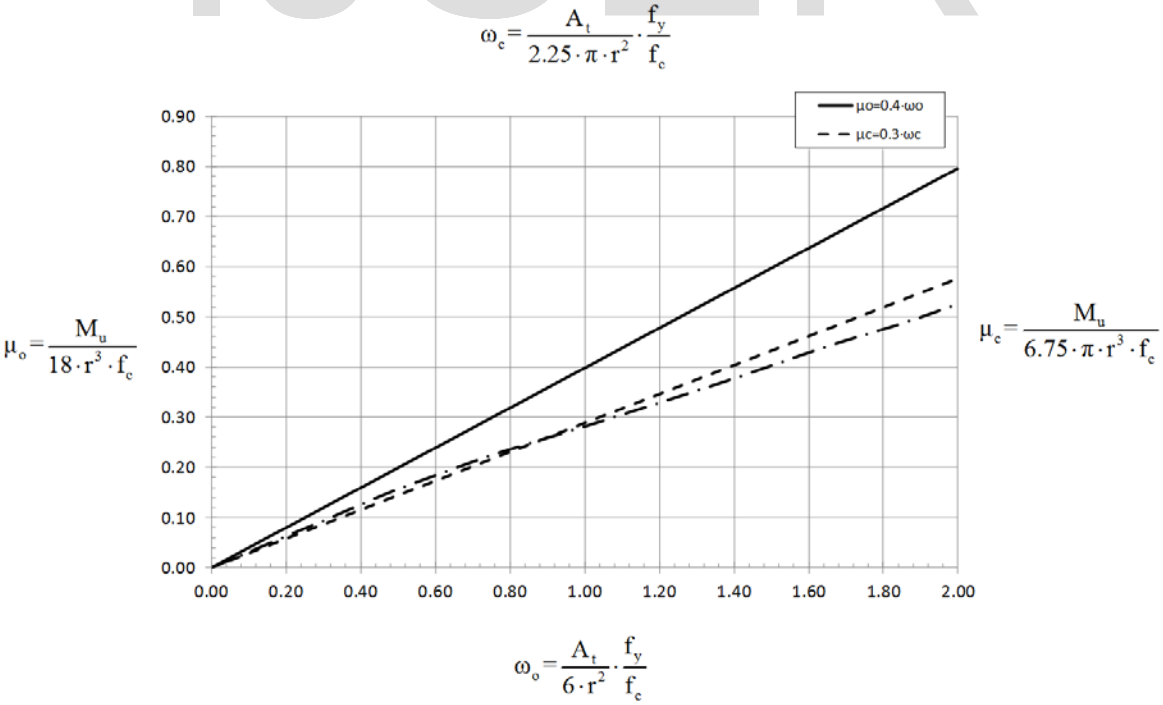


Fig. 10 Diagram for an approximate calculation of sections with interlocking spirals on the basis of the proposed substitute sections: (a) cyclical (for bending) and (b) rectangular (for bending and shear) cross-sections.

5.2 Specimen 3

The mechanical behavior of specimen 3 under cyclic lateral loading (seismic type of loading) is shown in Fig. 11 in the form of load versus displacement hysteresis loops.

The shape of hysteresis loops point out to the following:

1. Specimen's strength was maintained unabated, taking also into consideration the P-δ effect, even at the ultimate displacements of 45mm. Due to this displacement the inclination of the specimen axis was 8%.
2. The influence of slippage of the reinforcement is negligible, taking into account that this would cause hysteresis loop pinching (narrowing of the hysteresis loops especially near the zero displacement point) in the load versus displacement diagram of the specimens. This signifies that the cyclic shear had no deteriorating influence upon the interlock of the two spirals.
3. The energy dissipation capacity illustrated as the area of the successive hysteresis loops in the P versus δ diagram is progressively increasing as deformation increases and this is reckoned to be an important advantage of earthquake-resistant mechanical behavior.

A typical flexural failure, as shown in Fig. 8, was observed for specimen 3, as expected, on account of the low percentage of longitudinal reinforcement in comparison to the other two specimens, with which specimen 3 had equal amount of transverse reinforcement (Table 1). During the first cycle of loading, a passing-through flexural crack was developed at the fixed section of the column head. In the same phase, flexural-shear hairline cracks appeared along the column. With increasing cycles of loading, these flexural-shear cracks were minimally widened or developed (longitudinally) in contrast to the main flexural crack which kept increasing all the time (with simultaneous deterioration of the compressed zone).

It is noteworthy that the 35 mm spacing between centers of spirals satisfies the minimum requirement of the Greek Concrete Code, which specifies that the spacing s in question should not exceed 20% of the diameter of the cyclical cross-section core.

6 CONCLUSIONS

The test results, as well as the analytically derived values of this study which is the "pilot" of a wider Research Program, result to the following conclusions:

1. In the case of ensuring the interlock of spirals according to the internationally accepted minimum requirements for secure interlock, the strength of the complex section was found to be approximately equal to the sum of the strengths of the two single cyclical overlapped sections.
2. The first experimental results confirm the corresponding values approximately calculated on the basis of the substitute cross-sections, of an enveloping perimeter.
3. Structural elements of a rectangular section with interlocking spirals when subjected to seismic type loading have shown an excellent performance from a mechanical behavior stand point.

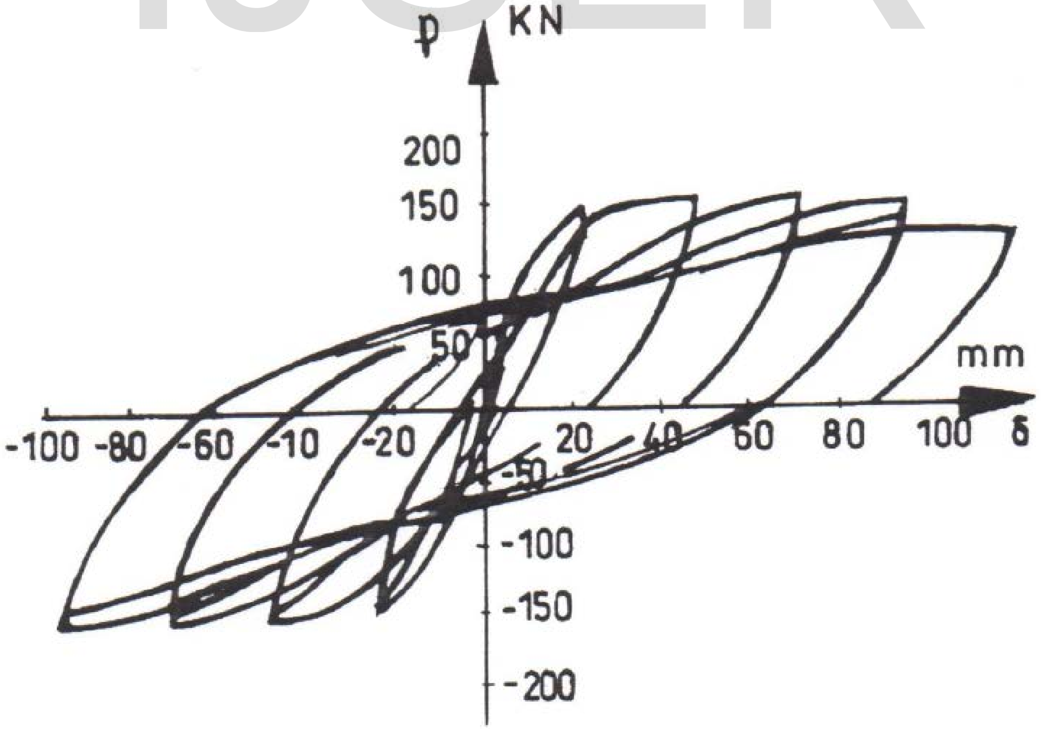


Fig. 11 Seismic response diagram of specimen 3.

REFERENCES

[1] ACI Committee 318, *Building Code Requirements for Structural Concrete (ACI 318-99) and Commentary (ACI 318R-99)*. USA: American Concrete Institute, 1999.

[2] Concrete Design Committee P3101, *NZS 3101:2006, Concrete Structures Standard: Part 1 - The Design of Concrete Structures*. Wellington, New Zealand: Standards Council, 2006.

[3] M.J.N. Priestley, *Strength and Ductility of Bridge Substructures*. New Zealand: Road Research Unit, National Roads Board, 1984.

[4] American Association of State Highway and Transportation Officials, *AASHTO: Standard Specifications for Highway Bridges (17th Edition)*. Washington D.C.: Association General Offices, 2002.

[5] H. Tanaka, "Effect of Lateral Confining Reinforcement on the Ductile Behaviour of Reinforced Concrete Columns," PhD dissertation, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 1990.

[6] H. Tanaka and R. Park, "Strength and ductility of reinforced concrete columns with interlocking spirals," *Proceedings of 10th World Conference on Earthquake Engineering*, Madrid, Spain, 1992.

[7] J.F. Correal, M.S. Saiidi, D.H. Sanders and S. El-Azazy, "Analytical Evaluation of Bridge Columns with Double Interlocking Spirals," *ACI Structural Journal*, vol. 104, no. 3, pp. 314-323, May 2007.

[8] H.G. Kwak, C.K. Choi and G.T. Chung, "Direct Search Approach to Optimal Spiral Column Design," *Engineering Structures*, vol. 18, no. 5, pp. 371-377, May 1996.

[9] Q. Li and A. Belarbi, "Seismic Behavior of RC Columns with Interlocking Spirals under Combined Loadings Including Torsion," *Procedia Engineering*, vol. 14, pp. 1281-1291, 2011.

[10] D.I. McLean and G.C. Buckingham, "Seismic Performance of Bridge Columns with Interlocking Spiral Reinforcement," Technical Report WA-RD 357.1, Washington State Transportation Center (TRAC), Washington State University, Pullman, Washington, Sept. 1994.

[11] J.F. Correal, M.S. Saiidi and D.H. Sanders, "Seismic Performance of RC Bridge Columns Reinforced with Two Interlocking Spirals", Technical Report CCEER-04-06, Center for Civil Engineering Earthquake Research, University of Nevada, Reno, Nevada, Aug. 2004.

[12] G. Benzoni, M.J.N. Priestley and F. Seible, "Seismic Shear Strength of Columns with Interlocking Spiral Reinforcement," *Proceedings of 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, 2000.

[13] J. Kim and C. Park, "The Behaviour of Concrete Columns with Interlocking Spirals," *Engineering Structures*, vol. 21, no. 10, pp. 945-953, Oct. 1999.