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Reinforced concrete beam-column joints with lap splices under cyclic loading

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Abstract. Experimental results are presented from tests conducted on reinforced concrete beam-column joints with lap splices under reversed cyclic loading simulating earthquake action. Response curves are compared for twenty-four specimens designed according to Eurocode 2. The main parameters of the investigation are, the geometry of the reinforcing bar extension, the applied axial load (normalized), the available cover over lap splice region extended as length required from Eurocode 2, as well as the shape and the volumetric percentage of the stirrups confining the lap splice zone. The results are evaluated with regards to the load intensity, the energy absorption capacity and the characteristics of the load deflection curve.

Key words: reinforced concrete; joints; beam-column connections; lap splices; bond; cyclic load; Eurocode 2.

1. Introduction

Lap splices are the most familiar and economic way of extending reinforcing bars and is almost always used in common reinforced concrete structures. This is dictated by the demand for great length of continuous reinforcement in reinforced concrete structures, as well as by segmental construction procedures. At connections with overlapping, the steel bars usually are in contact and bond in the surrounding concrete is relied upon transferring the forces between the overlapping bars. Because of the detrimental effect bond failure would have on the performance of splice regions, these connection zones are generally acknowledged to be points of reduced capacity, especially when cyclic loading at large deformation demands is imposed (such as in the case of an earthquake). Indeed from reconnaissance reports it appears that damage is frequent in splice zones during seismic excitation. The most common use of lap splices in columns of multi-storey frame structures is directly above the floor slabs i.e., within the critical zones of columns where the maximum value of bending moment occurs during lateral sway (Fig. 1).

Recent Design Codes (ACI Committee 318, 1995; Canadian Standards Association, 1984; EC2-Eurocode 2, ENV 1992; EC-8-Eurocode 8, ENV 1998-1-3-1994) include characteristic provisions for lap splices in reinforced concrete structures in order to ensure load capacity, ductility and

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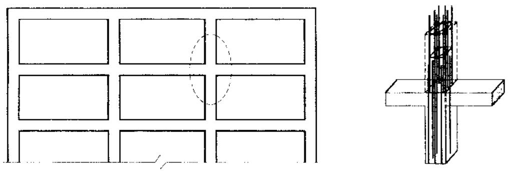
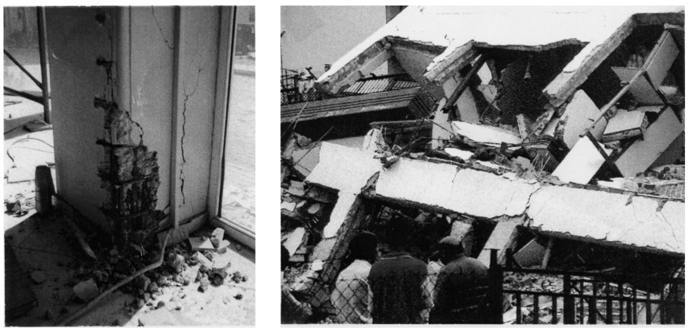


(a) Typical internal joint



(b) Lapsplice failure (Athens earthquake 1999)

Fig. 1 Joints of multi storey frame structures with lap splices

continuity of the constructed members. Most of these Design Codes under seismic actions prohibit or discourage splicing steel bars in the regions where plastic hinges are expected to occur such as beam-column joints. Generally it is recommended that splicing should be located at regions such as the mid height of the column. At the same time with additional requirements, the Codes aim to overdesign the lap splice regions in order to avoid unpredicted mechanisms of failure.

However from field experience it appears that despite the recommendations lap splices are often located at critical zones, due to construction simplicity. On the other hand the existing lengths of the lap splices frequently do not satisfy the demands of the valid Code.

The available experimental literature reports primarily on the mechanical behavior of lap splices designed according to the ACI or CSA Codes, reflecting primarily North American Practice. Typical load histories that have been used in the tests comprise either a large number of cycles of relatively small intensity or a small number of cycles covering a great range of intensity (Lukose *et al*. 1982, Panahshahi *et al*. 1992, Paulay and Priestley 1992, Paulay 1982, Rezansoff *et al.* 1988, Sagan *et al*. 1991).

With regards to more recent regulations, such as the Eurocodes (ENV 1992, ENV 1998-1-3-1994) even less experimental information is found. Particularly lacking is the information on the separate influence of several important design parameters, such as the lap length, the geometry of the end of the lengthened steel bars (e.g., provision for special hooks) and the type and amount of confinement.

This paper reports results from an experimental study involving twenty-four beam-column connection specimens. Lap splices of various geometries were considered adjacent to the joint region. Specimens were subjected to large amplitude pseudo-static cyclic excitations. Results are evaluated in light of the test variables.

2. Experimental investigation

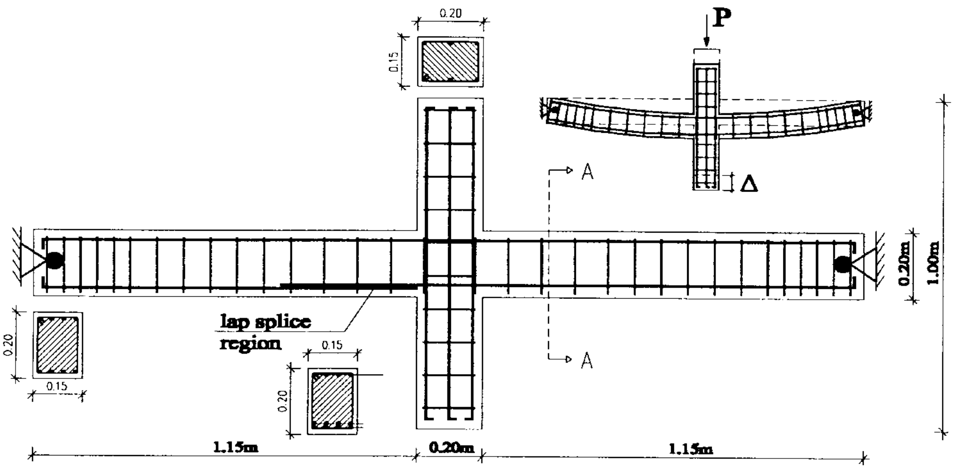
2.1 Description of test specimens

Test specimens with the geometry and dimensions of Fig. 2(a) were designed to represent a typical beam-column connection of a multistory frame building. The parameters that were investigated in this experimental study were as follows:

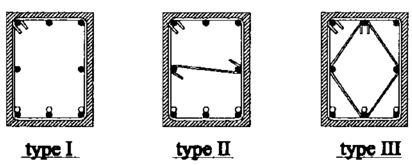
- The geometry of the end anchorage of the steel bars in the lap splice region (straight or hooked end).
- The applied axial load normalized with respect $n = N/fc'bh$; where bh is the cross section area. The values of n considered were 0, –0.1, –0.2, –0.3.
- Arrangement (geometry) of confining reinforcement in the lap splice regions. Three different patterns of stirrup arrangement were used according to Fig. 2(b).
- The volumetric ratio of lateral reinforcement, in conjunction with the stirrup bar diameter used and spacing between stirrups.
- The lap length provided, as a fraction of the required length for lap splices according with the Eurocode 2 (EC-2, ENV 1992).

The EC-2 specifies that the required lap length l_s, for extension of steel reinforcing bars can be calculated from the following expression:

$$l_s = l_{b,net} \cdot a_1 \geq l_{s,\min} \tag{1}$$



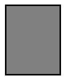
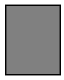
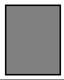
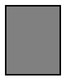
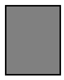
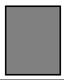
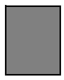
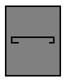
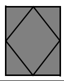
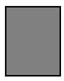
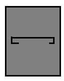
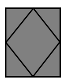
(a) Specimen's details



(b) Shape of stirrups

Fig. 2 Overall dimensions and cross sections of specimens

Table 1 Test specimens details

No		normalized axial force *n*	Lap splice			Stirrups			Concr. Strength f_{cm} (Mpa)
			Bar Diameter (mm)	Kind	$l_s/l_{b,\,net}$ (Length, mm)	Shape	Kind	Volumetric ratio ω_w	
1	2	3	4	5	6	7	8	9	10
1	K-O-SI	0.00		-	-		Ø6/100	0.0058	
2	K-O-DI	0.00		-	-		Ø6/50	0.0117	
3	K-S-SI	0.00			1.00		Ø6/100	0.0058	
4	K-S-DI	0.00	8		(670)		Ø6/50	0.0117	26.8
5	K-H-SI	0.00			1.00		Ø6/100	0.0058	
6	K-H-DI	0.00			(540)		Ø6/50	0.0117	
7	K-S-DI(1)	–0.10					Ø6/50	0.0117	
8	K-S-DI(2)	–0.20			1.00		Ø6/50	0.0117	
9	K-S-DI(3)	–0.30			(670)		Ø6/50	0.0117	
10	K-H-DI(1)	–0.10	8				Ø6/50	0.0117	26.8
11	K-H-DI(2)	–0.20			1.00		Ø6/50	0.0117	
12	K-H-DI(3)	–0.30			(540)		Ø6/50	0.0117	
13	K-S'-SI	0.00					Ø8/100	0.0104	
14	K-S'-DI	0.00					Ø8/50	0.0208	
15	K-S'-SII	0.00			0.50		Ø8/100	0.0126	
16	K-S'-DII	0.00	10		(380)		Ø8/50	0.0251	41.0
17	K-S'-SIII	0.00					Ø8/100	0.0178	
18	K-S'-DIII	0.00					Ø8/50	0.0357	
19	K-H'-SI	0.00					Ø6/100	0.0058	
20	K-H'-DI	0.00					Ø6/50	0.0170	
21	K-H'-SII	0.00			0.50		Ø6/100	0.0071	
22	K-H'-DII	0.00	8		(207)		Ø6/50	0.0142	41.0
23	K-H'-SIII	0.00					Ø6/100	0.0100	
24	K-H'-DIII	0.00					Ø6/50	0.0201	

Column
1: specimen number
2: specimen code
3: axial force (normalized)
4: bar diameter
5: lap splice kind
6: ratio of existing lap splice length to required
7: stirrups shape
8: stirrups diameter, space
9: stirrup volumetric ratio

where,

$l_{b,net} = \alpha_\alpha l_b \frac{A_{s,req}}{A_{s,prov}} \geq l_{b,\min}$ = the required anchorage length,

α_1 = efficiency coefficient, (α_1 = takes on values 1.0, 1.4, and 2.0) depending on the percentage of bars overlapping at the same section, and also accounts for the top bar effects. In this application, $\alpha_1 = 2.0$.

$l_b = \frac{\varnothing f_{yd}}{4 f_{bd}}$ = basic anchorage length,

$A_{s,req}$, $A_{s,prov}$ = the required by design and the actually provided area of reinforcement respectively. For earthquake design $A_{s,req}/A_{s,prov} = 1.0$.

α_a = coefficient of effectiveness of anchorage (1.0 for straight ends, 0.7 for hooked curved bars in tension when the concrete cover is at least 3$\varnothing$).

$l_{s,\min}$ = minimum lap length ($l_{s,\min} \geq 0{,}3.\alpha_\alpha \alpha_1 l_b > 15\varnothing > 200$ mm)

$\varnothing$ = bar diameter

Deformed steel bars were used both for longitudinal and transverse reinforcement. The lap splices were located on only one side of the “column” of the connection (Table 1, Fig. 2). This configuration was selected to evaluate the different mechanical behaviour between the sides with and without bar lapping.

Two of the specimens (No1 and No2), examined had also continuous bars throughout (no lap splices). These specimens will be used in the remainder as reference. Details for all specimens are presented in Table 1.

The connections were tested under large amplitude, reversed cyclic deformation. Fig. 3 depicts a typical history of imposed deformation that corresponds to a relative storey drift for the building with increasing intensity equal to $\Delta x/h$ = 0.2, 0.4, 0.8, 1.6, 3.2 and 4.8%. The displacement of the joint was controlled during the test using a hydraulic actuator. A system of rollers was used for the pin-jointed supports. Axial load was applied initially and subsequently sustained throughout the duration of the test. Loads and deformations were recorded with electrical transducers (Fig. 4). Two types of concrete were used. The values of the concrete strength f_c were experimentally estimated from cylinder specimens, 150 × 300 mm (Table 1).

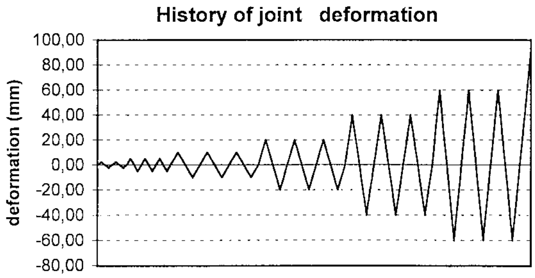
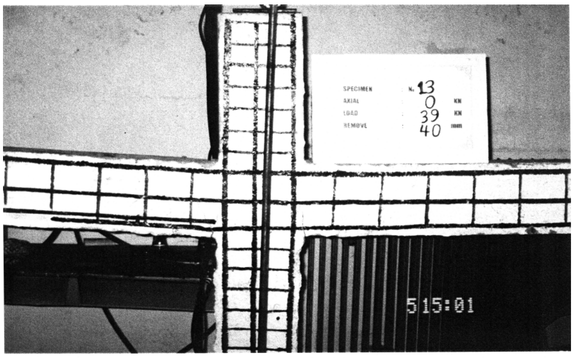
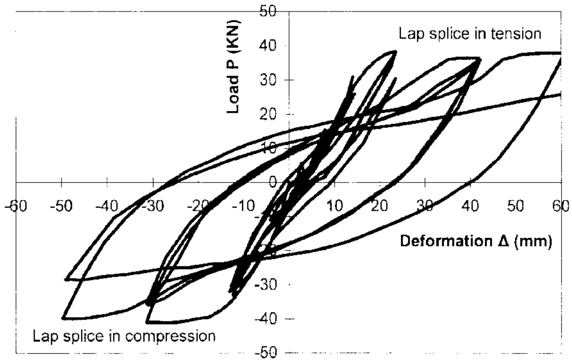


Fig. 3 Typical history of joints displacements

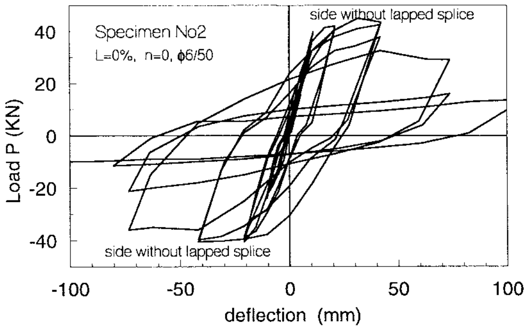


(a) During the test

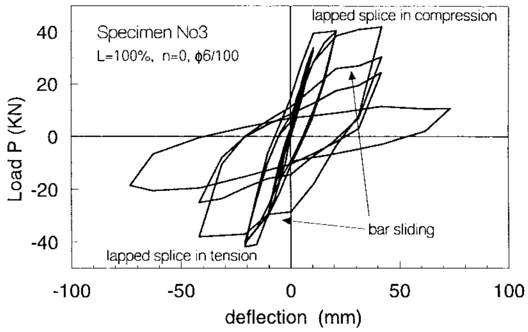


(b) Load versus deflection for the middle point

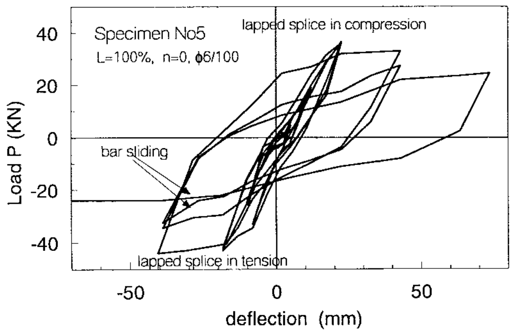
Fig. 4 Specimen No13



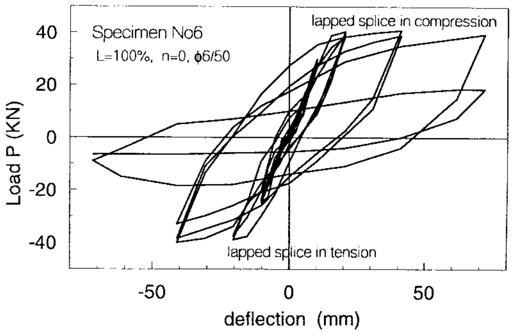
(a) Specimen No 2(K-O-DI, without lengthening)



(b) Specimen No 3(K-S-SI)



(c) Specimen No 5(K-H-SI)

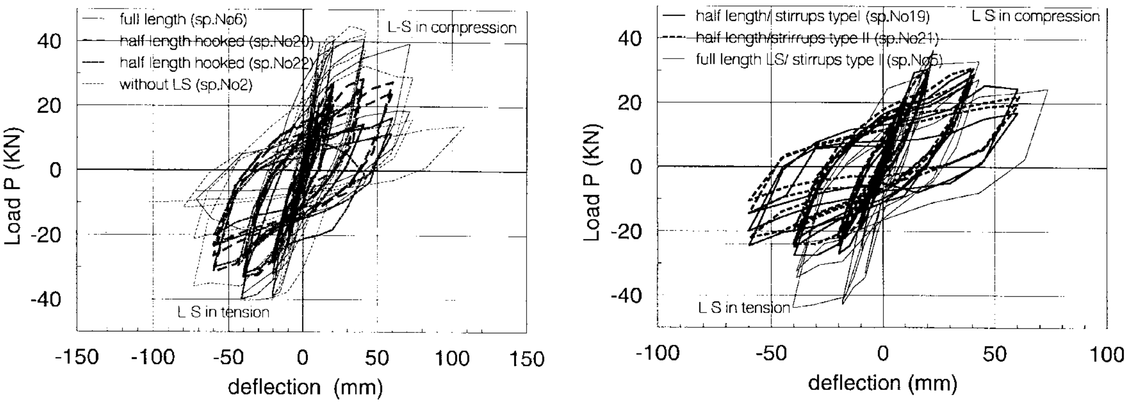


(d) Specimen No 6(K-H-DI)

Fig. 5 Load versus deflection diagrams

2.2 Experimental results

For the specimens with full lap length, the observed response of the specimens was satisfactory. Most of them failed when cracking and collapse of the concrete mass occurred, showing ductile behavior with relatively small values of divergence amongst them for the limit states of cracking and yielding. On the contrary, at the loading cycles after the maximum load was imposed, the divergence was greater.



(a) Stirrups φ8/50 (b) Stirrups φ6/100

Fig. 6 Comparison of the mechanical behavior of specimens with, without and 50% reduced lap length

A progressive reduction of stiffness was observed for large values of deformation, especially after yielding, with simultaneous rapid increase of the absorbed energy (Fig. 5). At the same time, due to the cyclic load reversals in some specimens at the final stages, a sliding of the main reinforcement occurred in the lap splice region. This sliding was responsible for the "pinching" that is evident in the load deformation (P-Δ) diagram, and caused spalling of the cover over the longitudinal reinforcement. Also, obvious was the differentiation of the residual stiffness between specimens, which appears to be principally affected by the type of the lap splice used. The influence of each of the examined parameters on the characteristics of the recorded P-Δ relationship is as follows:

a. Lap length

All specimens in which the lap length was according to the EC-2 requirements showed a satisfactory behavior without significant loss of resistance. Non-ductile behavior due to lap splice failure was not observed in any of the specimens with full lap length. Note that failure occurred in these specimens after the steel reinforcement yielded from the side without the lap splice. In some lightly confined splice cases with straight end bars (specimens No3 and No5 with stirrup volumetric ratio ω_w = 0.0058) a slight degree of "pinching" was observed in the P-Δ diagram at very large deformations, which is characteristic of steel reinforcement sliding (Fig. 5b and Fig. 5c). In the specimens with provided lap lengths half the values prescribed by the code, the phenomenon of sliding was much more intense.

The mechanical behavior of specimens with reduced lap splice lengths and the corresponding ones with or without full lap splice are compared in Fig. 6.

The ultimate load carrying capacity for the specimens with reduced lap splice ranged between 0.55 and 0.75 of the corresponding value for full lap splice. This behavior was depended on the shape of bar end and the mode of loading (tension-compression) in the lap spliced side.

b. Axial load

The presence of axial load influenced drastically the mechanical behavior of the lap splices (Fig. 7). For the examined cases of axial load (n = 0.0, –0.1, –0.2, and –0.3) it has to be noticed that:

- the specimen resistance (i.e., imposed load at a given displacement level) increased as the

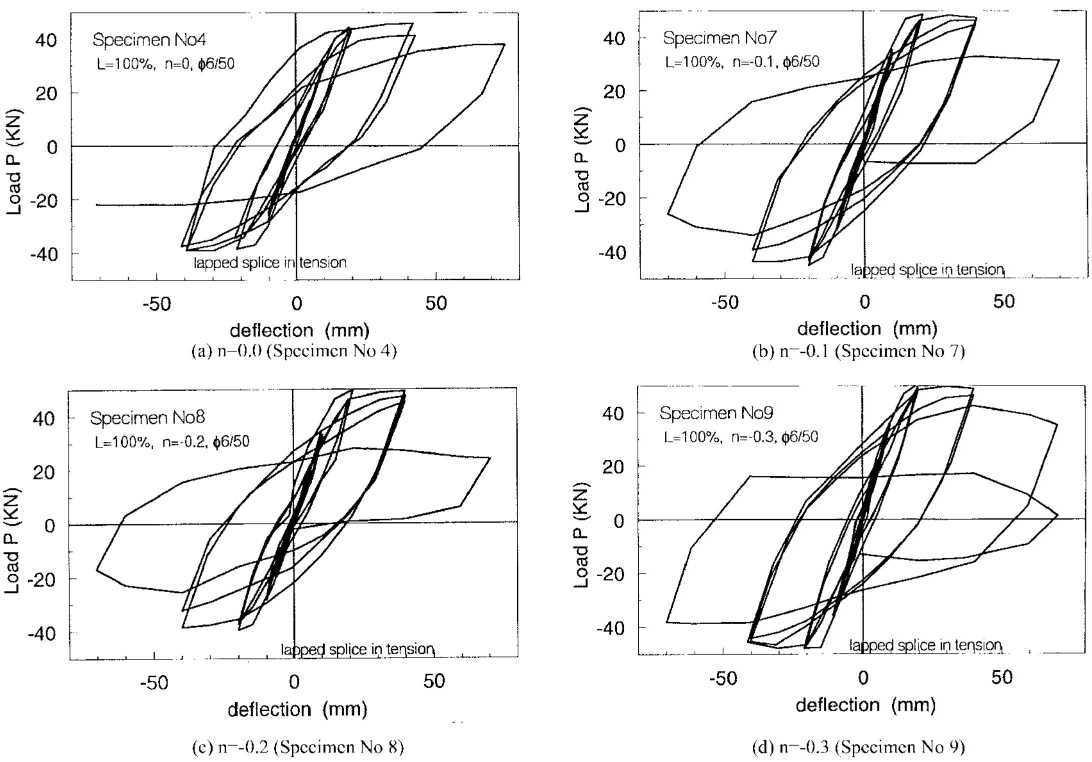


Fig. 7 Influence of axial load - specimens with straight end bars

compression axial load increased (reaching values of $n = -0.30$).

- the increase of the apparent stiffness which was observed under the tensioning of the lap splices was not quite visible for the specimens with axial loads (Fig. 7).
- the presence of axial load in the lap length region, resulted in a slower increase of resistance in the ascending branch, and a faster decay of the post-peak softening branch.

c. End type

By comparing the behavior of specimens with straight end bars with that of the corresponding ones with hooked end bars, it is concluded that the shape of the end of the spliced bar determined the characteristics of mechanical response and failure.

In Fig. 8(a), which presents the specimens with hooked end bars for the tensioning compared with the straight end corresponding ones, the increase in maximum tension load is obvious for hooked end bars. At the same time, the simultaneous increase of the imposed load for the connection with hooked end bars under compression was obvious. For the cases of the specimens with reduced lap length, the influence of the type of the end of lapped splice bar in conjunction with the amount of confinement (number of stirrups) significantly affected the observed sliding of these bars during alternation of the loading (Fig. 6). After the initial loading cycles, specimens with straight end bars and small confinement (No3, No5) showed pinching in P-Δ diagram. Through pinching, the absorbed energy per cycle was reduced although strength was unaffected. At the same time, the

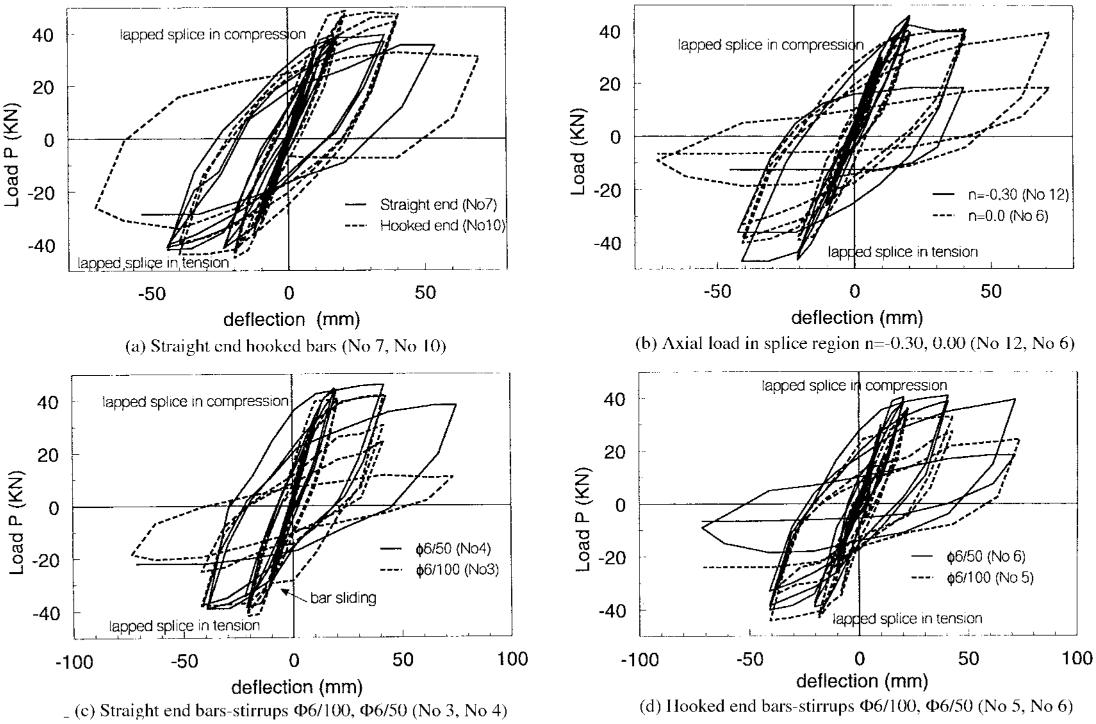


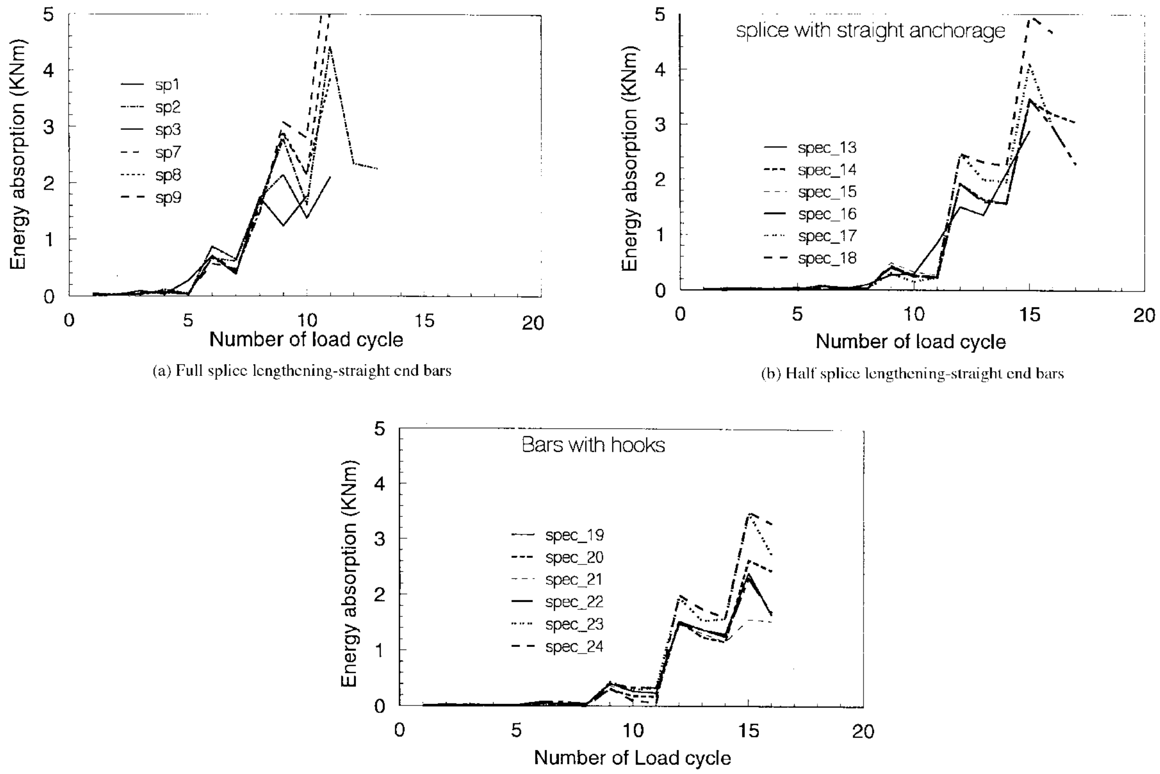
Fig. 8 Influence of variant parameters to formation the mechanical behavior of specimens

average value of stiffness remained low, even for low values of loading. Moreover, in the case of the straight end bars a relative sliding of the steel reinforcement appeared, from the initial loading cycles, with almost double the deformation and loading equal to 0.70 times the corresponding loading without lap splices.

For the specimens with half lap length (specimens No19 to No24), the use of hooked ends in the longitudinal reinforcement (Fig. 6a) improved the tension force developed at any given displacement level, to about 75% of the corresponding value for specimens without lap splices (i.e., an increase by 50% from the corresponding values of splices with straight ends-Fig. 6b). But throughout the interchange of the load sign, the load showed significant range fluctuation depending mainly on the lap length and on the type of the stirrups.

d. Confinement

In all the examined cases, the transverse reinforcement was one of the most important parameters for the formation of the lap lengths behavior in the imposed seismic action modeling. Specimens having a low quantity of stirrups at the splice regions, (ω_w = 0.0058, Table 1) presented a reduced resistance (in large deformation load cycles) with a great reduction of the absorbed energy (Fig. 8c,d). A better confinement (ω_w = 0.0117) improved the mechanical behavior by increasing (for the same deformation) the load capacity and the energy absorption. Also, the increase of the confinement (bars with greater diameters, different stirrup shapes but mainly the smaller distances between them) had reduced the relative sliding of the steel bars (Fig. 8c, d). The influence of the distance between the bars of lateral reinforcement, has appeared in the examined cases to be greater under the



(a) Full splice lengthening-straight end bars

(b) Half splice lengthening-straight end bars

(c) Half splice lengthening-hooked end bars

Fig. 9 Energy absorption per load cycle - joints with half lengthening splice

compression of the overlapping steel bars, than under tension. This fact was due to the lateral dilatation of the compression zone and its consequence, lateral pressure of the lap length region due to the tension of the stirrups and the smaller buckling length of the longitudinal bars.

The specimens that had stirrups type I or type II, practically presented the same behavior. On the other hand, stirrups of type III giving an increased confinement, differentiated the undertaken load for that specific deformation, decreased the relative movement of the reinforcement bars mainly when large values of deformations were met.

e. Energy absorption

The absorbed energy per loading cycle - measured by the area encompassed by the load-displacement curve and displacement axis - for small deformations ($d < 200$ mm, relative displacement < 1.7%) was practically 'not dependent' on the type of the lap splice and the stirrups percentage as there were small differences between the specimens. On the contrary, for large deformations, a differentiation of the absorbed energy per loading cycle was present, depending on the confinement and on the level of the axial load (Fig. 9). After the initial loading cycles, important differences occurred as far as the percentage of the absorbed energy per cycle was concerned. Energy depended on the confinement and the bar lengthening type (Fig. 9b).

At the same time, during the first cycle of each loading group, with same displacements, the energy absorption was 15-25% greater than the corresponding displacement of the next cycles. For the specimens with stirrups of type II, the absorbed energy per loading cycle, practically remained the same with the corresponding samples of stirrups of type I, while the corresponding one of the specimens which had stirrups of type III, presented an increase about 30%.

4. Conclusions

Experimental results obtained from the mechanical behavior of 24 reinforced concrete joints with lap splices in cyclic loading, designed according to EC-2, were presented. The most important conclusions obtained from this research results:

· In general, the mechanical behavior of the specimens with the full length of the considered lap splices, was satisfactory. Most of the beams presented a ductile behavior ($\mu = \delta u/\delta y$ = 2.0 to 3.7) with failure of the compressive zone of the concrete, due to large deformations after yielding of longitudinal bars.

· In some cases the side of the joint without lap splice failed first.

· Samples with lap lengths of straight bars equal to the half of that required by EC-2, presented sliding of the reinforcement.

· The existence of axial force for values of axial load $n \leq -0.30$, in some cases had improved the whole mechanical behavior, by increasing, for the same deformation, the load carrying capacity.

· Significant was also, the contribution of the shape of the ends of the lap spliced bars, especially for the cases of the samples with lap lengths equal to the half of the required one, where the existence of the hook reduced the sliding of the reinforcement.

· The increase of the confinement by stirrups impressively improved the mechanical behavior, as it reduced the relative sliding of the reinforcement bars, it increased the load carrying capacity for the same (large) deformation (about 10%), and it increased the ductility approximately 50% and the absorbed energy per joint 20 to 40%.

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Notation

α_1	: coefficient of overlapping "efficiency"
α_α	: coefficient of anchorage
$A_{s,\,cal}$	: area of required reinforcement
$A_{s,\,req}$, $A_{s,\,prov}$	: the area of reinforcement required by design and actually provided, respectively
b, h	: dimensions of the beam cross section
f_c	: compressive strength of concrete
f_{bd}	: design value for ultimate bond stress
l_s	: lap length
$l_{b,\,net}$	: required anchorage length
$l_{s,\,\min}$	: minimum lap length
N	: Axial load, negative = compression
n	: normalized axial load ($= N/bhf_c$)
P	: applied load
Δ	: joint deformation
$\varnothing$	: steel bar diameter