

EXPERIMENTAL INVESTIGATION ON THE BEHAVIOUR OF LAP SPLICES UNDER UNIAXIAL CYCLIC LOADING

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ABSTRACT

Splicing of longitudinal reinforcement in the plastic hinge region of reinforced concrete (RC) members was common practice in buildings and bridges before the introduction of capacity design principles. Experimental and field observations showed that the presence of lap splices in regions where inelasticity concentrates might lead to a significant reduction of both the strength and the displacement capacity of the structural member. The behaviour of this constructional detail depends on a number of factors, which should ideally be considered when simulating the response of RC members. However, models describing the full hysteretic response of lap splices are currently lacking. Their future development, calibration, and validation depend on the existence of reliable and comprehensive experimental data.

Following previous research at the *École Polytechnique Fédérale de Lausanne* on the seismic performance of existing, poorly detailed bridge piers, this paper describes a new experimental programme on lap splices. The goal is to investigate the influence of splice length, confining reinforcement, and loading history on the behaviour of lap splices, which are among the parameters affecting their response. The test units represent the boundary elements of bridge piers or walls and are tested under axial tension-compression cyclic loading. Their geometry, test setup, and instrumentation are herein described as well as the first preliminary results. Particular attention is drawn to the different failure modes and to the influence of confining reinforcement on the performance of lap splices.

Keywords: Lap splices; Cyclic loading; Loading history; Experimental tests; Confining reinforcement.

1. INTRODUCTION

The presence of lap splices in RC members may considerably reduce their strength and ductility capacity, especially if located in regions where inelastic deformations are largest such as plastic hinges. In the framework of a research project on the seismic safety of existing Swiss bridges, Bimschas (2010) and Hannewald (2013) tested six RC bridge piers, of which three featured spliced longitudinal reinforcement in the plastic hinge region, and three were reference units with continuous longitudinal reinforcement. While the specimens with spliced reinforcement did not show an evident reduction in force capacity, they depicted a significant reduction in displacement ductility of up to 50% with respect to the corresponding reference units.

Previous research mainly focused on the evaluation of the strength (e.g. Canbay and Frosch 2005; Orangun et al. 1977; Zuo and Darwin 2000) rather than the displacement capacity of lap splices, which is of fundamental importance for displacement based assessment of RC structures featuring this

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constructional detail. Moreover, models characterizing the full hysteretic response of lap splices as function of the main parameters influencing their behaviour are currently lacking. Such relationship would be a much-needed tool to simulate the response of spliced RC members; however, experimental data are required for its development, calibration and validation.

On a recent study on the influence of lap splices on the inelastic behaviour of RC walls, Almeida et al. (2017) and Tarquini et al. (2017) identified the lap splice length, confining reinforcement and loading history as the main parameters affecting the ductility of those members.

This paper presents an experimental programme, described in section 2, which aims at investigating and quantifying the influence of the above-mentioned parameters on the cyclic response of lap splices. A selection of the preliminary results is showed in section 3, while some final remarks are included in section 4.

2. EXPERIMENTAL PROGRAMME

In order to characterize the hysteretic behaviour of lap splices, an experimental programme is being carried out at the structural laboratory of the *École Polytechnique Fédérale de Lausanne* (EPFL). The test units (TU) represent the boundary element of bridge piers/walls with lap splices in the plastic hinge region, and are subjected to uniaxial tension-compression loading. The geometry and reinforcing layout of test units are described in subsection 2.1, an overview of the entire test matrix is given in subsection 2.2, material properties are presented in subsection 2.3, and finally the test setup, instrumentation and loading protocol are shown in subsection 2.4.

2.1 Description of the test units

The test units share the same geometry, consisting of a 200×200 mm square cross section and a height of 1260 mm (Figure 1). They are casted with a foundation and top beam RC blocks of dimensions 550×550×300 mm, required to anchor the column longitudinal rebars and used to clamp the specimens to the testing machine. The longitudinal reinforcement is spliced above the foundation interface and consists of Ø14 mm rebars; the splice length is a variable parameter of the test campaign.

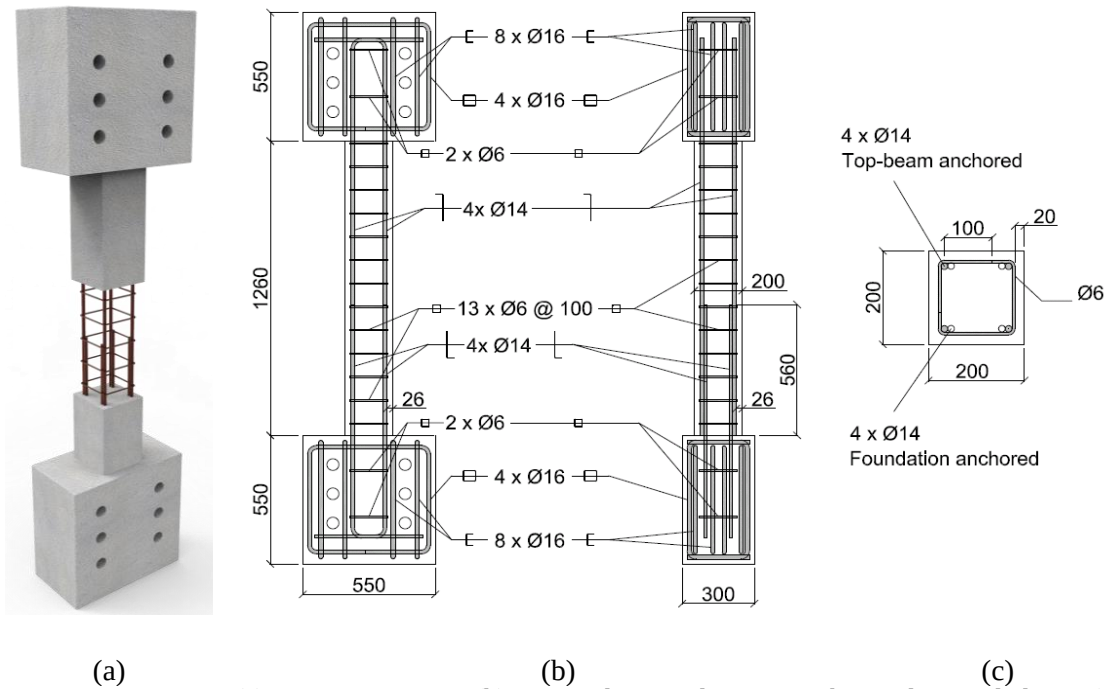


Figure 1. LAP-P1: (a) 3D representation; (b) Sectional views along two orthogonal vertical planes; (c) Cross section (dimensions in millimetres).

Two reference units with continuous reinforcement along the entire boundary element length are included as well (LAP-C1 and LAP-C2). The transverse (confining) reinforcement is similar to the

one proposed by Bimschas (2010) and Hannewald (2013) in their large scale piers tests. It consists of Ø6 mm diameter stirrups closed by 90° hooks, representative of Swiss construction practice prior to the introduction of seismic standards. The spacing of the confining reinforcement is another variable parameter of the experimental programme, as shown later in Table 1.

2.2 Test matrix

The experimental programme involves the test of 24 specimens (Table 1). The main parameters investigated, which are among the most impactful on the ductility capacity of lap splices (Almeida et al. 2017; Tarquini et al. 2017), are the lap splice length l_s , the confining reinforcement ratio ρ_w , and the loading history LH . Four different lap splice lengths are considered, ranging from 25 to 60 times the longitudinal bar diameter ($\phi_l = 14$ mm). The upper and lower bounds are representative of modern code-compliant rules ($l_s = 60\phi_l$), and existing poorly detailed ($l_s = 25\phi_l$) construction practice, respectively. Five different confining reinforcement ratios ($\rho_w \in [0.1-0.3\%]$) are accounted for, as well as two benchmark test units with no confining reinforcement. Finally, five cyclic and one monotonic loading protocols are applied, as explained in further detail in subsection 2.4.

At the moment of the submission of the present manuscript the test programme is ongoing. The test units still to be tested are identified with an asterisk in the label column of Table 1.

Table 1. Test matrix

Label	h [mm]	b [mm]	l_s [mm]	Reinforcement				LH
				Longitudinal	ρ_l	Transverse	ρ_w	
LAP-P1	1260	200	560	4×Ø14	~1.5%	Ø6@100	~0.3%	C1
LAP-P2	1260	200	560	4×Ø14	~1.5%	Ø6@300	~0.1%	C1
LAP-P3	1260	200	560	4×Ø14	~1.5%	Ø6@200	~0.15%	C1
LAP-P4	1260	200	350	4×Ø14	~1.5%	Ø6@100	~0.3%	C1
LAP-P5	1260	200	840	4×Ø14	~1.5%	Ø6@300	~0.1%	C1
LAP-P6	1260	200	560	4×Ø14	~1.5%	Ø6@200	~0.15%	M
LAP-P7	1260	200	560	4×Ø14	~1.5%	Ø6@200	~0.15%	C1
LAP-P8	1260	200	560	4×Ø14	~1.5%	Ø6@200	~0.15%	M
LAP-P9	1260	200	560	4×Ø14	~1.5%	Ø6@200	~0.15%	C5
LAP-P10	1260	200	840	4×Ø14	~1.5%	Ø6@100	~0.3%	C1
LAP-P11	1260	200	350	4×Ø14	~1.5%	Ø6@200	~0.15%	C1
LAP-P12*	1260	200	350	4×Ø14	~1.5%	Ø6@300	~0.1%	C1
LAP-P13*	1260	200	840	4×Ø14	~1.5%	Ø6@200	~0.15%	C1
LAP-P14*	1260	200	840	4×Ø14	~1.5%	[-]	0	M
LAP-P15*	1260	200	560	4×Ø14	~1.5%	[-]	0	M
LAP-P16	1260	200	560	4×Ø14	~1.5%	Ø6@150	~0.2%	C1
LAP-P17	1260	200	560	4×Ø14	~1.5%	Ø6@120	~0.25%	C1
LAP-P18*	1260	200	700	4×Ø14	~1.5%	Ø6@200	~0.15%	C1
LAP-P19*	1260	200	560	4×Ø14	~1.5%	Ø6@120	~0.25%	C1
LAP-P20*	1260	200	560	4×Ø14	~1.5%	Ø6@120	~0.25%	C2
LAP-P21*	1260	200	560	4×Ø14	~1.5%	Ø6@120	~0.25%	C3
LAP-P22*	1260	200	560	4×Ø14	~1.5%	Ø6@120	~0.25%	C4
LAP-C1	1260	200	[-]	4×Ø14	~1.5%	Ø6@200	~0.15%	C1
LAP-C2*	1260	200	[-]	4×Ø14	~1.5%	Ø6@100	~0.3%	C1

*Specimen not yet tested; h : specimen height; b : cross section width; l_s : lap splice length; ρ_l : longitudinal reinforcement ratio; ρ_w : confining reinforcement ratio; LH : loading history type.

2.3 Material properties

2.3.1 Concrete

The 24 test units of the experimental campaign were casted in six series of four specimens each. A standard concrete mix (class C25/30) with a maximum aggregate size of 16 mm was used, which was intended to resemble the concrete employed for the large scale bridge pier tests conducted by Bimschas (2010) and Hannewald (2013). The concrete compression strength f'_c was derived from tests on cylinder samples with diameter 150 mm and height 300 mm, according to the Swiss standard SIA (1989). The results of the material tests are given in Table 2.

Table 2. Concrete strength derived from compression tests on cylinders according to SIA (1989).

Test units	LAP					
	P1-2-3, C1	P4-5-7-9	P6-8-10, C2	P11-12-13-14	P15-16-17-18	P19-20-21-22
f'_c [MPa]	31.7	30.4	31.6	33.1	34.4	N/A

f'_c : concrete cylinder compressive strength, determined from 3 tests per casting series; N/A: not yet tested.

2.3.1 Steel

The strength and ductility properties of the reinforcing steel are provided in Table 3. A ductile steel of type S500C (SIA 262 2004), depicting a yield plateau and an ultimate to yield strength ratio $f_u/f_y > 1.25$, was used for the longitudinal reinforcement. Cold-formed micro-alloyed steel, without yield plateau, was instead employed for the transverse (confining) reinforcement.

Table 3. Mechanical characterization of rebars from tensile tests.

Reinforcement type	f_y [MPa]	f_u [MPa]	ϵ_y [%]	ϵ_h [%]	ϵ_u [%]
Longitudinal (Ø14 mm)	510	635	0.33	0.95	9.3
Transverse (Ø6 mm)	475	625	0.25	0.25	9.8

f_y : steel yield strength; f_u : steel ultimate tensile strength; ϵ_y : steel yield strain; ϵ_h : steel strain at hardening onset; ϵ_u : steel strain at ultimate strength.

2.4 Test setup, instrumentation, and loading protocol

The test setup used in the experimental campaign is showed in Figure 2a. The test units are clamped at the top-beam and foundation levels to two T-shaped steel profiles, which are then pre-stressed to the testing machine. The latter is a uniaxial press, with a stroke of ± 125 mm and a force capacity of 2.5 and 10 MN in tension and compression, respectively. The mobile piston is located at the base of the machine, while the top section remains fixed throughout the duration of the tests.

The instrumentation is similar for all the test units and includes a composite system of light-emitting diodes (LEDs) and linear variable differential transformers (LVDTs) for the measurement of absolute and relative displacements (see below), and one load cell.

The LEDs are attached to the north and south concrete surfaces of the specimens following gridlines spaced 100 and 50 mm in the vertical and horizontal directions (see Figure 2b). The three-dimensional displacement of each sensor is recorded with a high-precision optical triangulation measurement system (NDI 2009). Additionally, pairs of LEDs are glued on adjacent rebars along the lap splice length (Figure 2c), using localized holes left during casting at a spacing of 100 mm. Such arrangement permits to track the relative slip between the spliced bars as well as between each bar and the surrounding concrete.

Two sets of three LVDTs are mounted on the east and west sides of the test units. They are placed such that the joint base length of the two bottom LVDTs corresponds to the height of the LED row located just above the lap splice. Finally, four LVDTs connect through a plumb line system the corners of the foundation and top beam RC blocks (see Figure 2c), which are used to measure the displacement imposed to the boundary element.

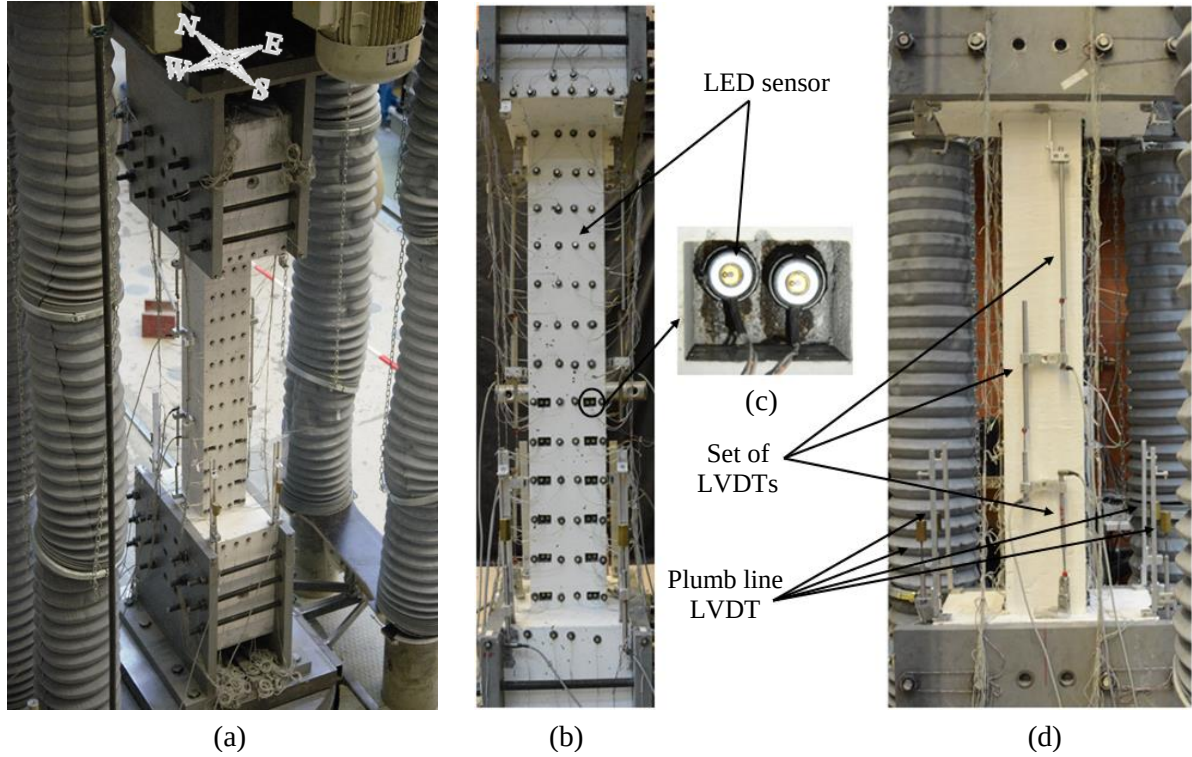


Figure 2. (a) Overview of the test setup; (b) LED grid on the N-S side of the TU; (c) Close-up of the LEDs glued on the spliced bars; (d) LVDTs on the E-W side of the TU and plumb-line LVDTs.

As discussed in subsection 2.2, one of the goals of the experimental programme is to investigate the effect of the loading history on the behaviour of lap splices. Different protocols are thus used for different test units, including tensile monotonic (M) and cyclic loadings (C1 to C5). The reference cyclic loading history (C1) is displayed in Figure 3, which is characterized by increasing displacement amplitudes in both tension and compression (ratio 1/10), and two cycles per displacement level. The ratio between tension and compression was determined based on the strains observed along the spliced region of the walls tested by Bimschas (2010) and Hannewald (2013), at the onset of splice failure. Loading history C1 is the only protocol considered in the present paper.

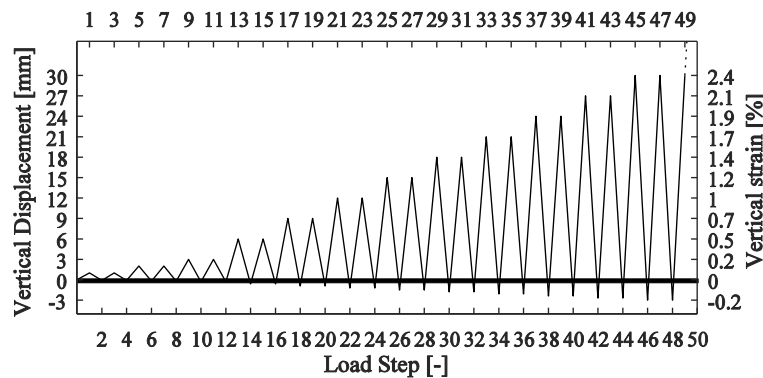


Figure 3. Main cyclic loading history (C1).

3. PRELIMINARY TEST RESULTS

In the next sections a selection of preliminary results of the tests performed so far are presented and discussed.

3.1 Force-displacement hysteresis

The force-displacement hysteresis of three groups of test units are displayed in Figure 4. Vertical imposed displacements Δ (y axis), computed as the average gauge length of the four plumb line LVDTs, are plotted as a function of the resisting axial force N (x axis).

In Figure 4a, the test units P1, P4 and P10 differed solely with respect to the lap splice length; they shared the same confining reinforcement ($\rho_w=0.3\%$) and were tested with the same loading protocol (C1). Although all the specimens reached the yield strength, the attained displacement capacity was considerably different. While in specimen LAP-P4 ($l_s=25\phi_l$) splitting failure of the splices occurred immediately after yielding at a displacement of $\Delta=4.5\text{mm}$, both LAP-P1 ($l_s=40\phi_l$) and LAP-P10 ($l_s=60\phi_l$) managed to sustain much larger displacement demands ($\Delta=24\text{mm}$ and $\Delta=27\text{mm}$ respectively). The combination of confining reinforcement and splice length of LAP-P1 proved to be a limit case: of the four column lap splices, three failed due to splitting cracks forming along the splice length while the last one failed due to rebar rupture occurring right above the lap splice. As for TU LAP-P10, which is the tested configuration with the longest and most confined splices, all four bars anchored at the top RC block fractured right above the lap splice region, where the largest crack formed (see next section for more details on the failure mode).

The confining reinforcement ratio ρ_w is the only variable for the five specimens reported in Figure 5b, which all have a lap splice length $l_s=40\phi_l$. Again, although all the test units reached the yielding force, their displacement capacity varied significantly with respect to the provided confining reinforcement. In particular, increasing ρ_w corresponds to an increase in the splice displacement capacity. This aspect will be discussed specifically in subsection 3.3.

The two test units depicted in Figure 4c are identical from the constructional point of view ($l_s=40\phi_l$ and $\rho_w=0.15\%$); however, LAP-P3 was subjected to the main cyclic loading protocol (C1) while LAP-P8 was tested under increasing tension force until failure (M1). It is apparent that the cyclic degradation plays a role on the displacement capacity of lap splices. In fact, LAP-P8 sustained almost twice the displacement imposed to LAP-P3 before failure.

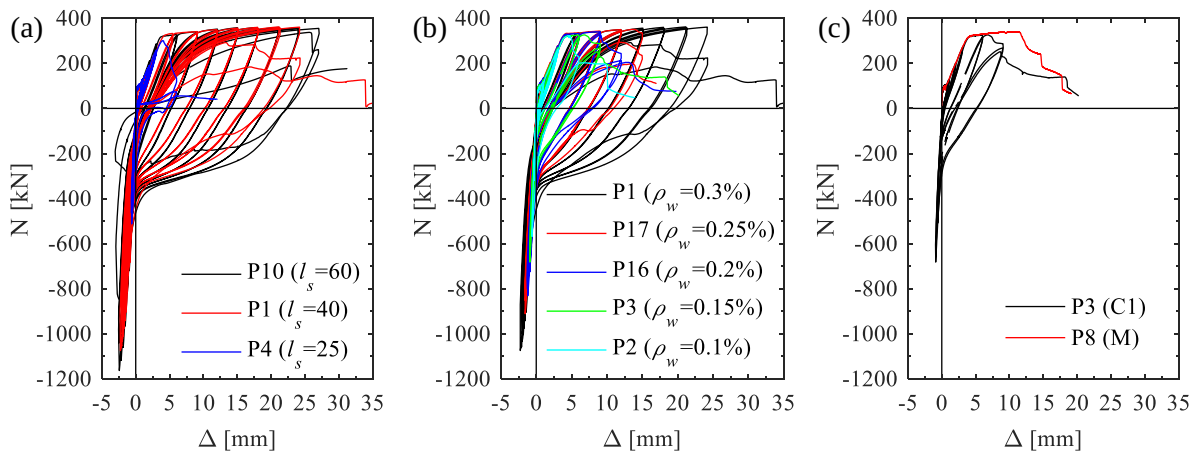


Figure 4. Force-displacement response of three TU subsets: (a) LAP-P1, P4 and P10, which differ only with respect to the splice length; (b) LAP-P1, P2, P3, P16 and P17, with distinct confining reinforcement ratios; (c) LAP-P3 and P8, for which different loading histories were applied.

3.2 Observed failure modes

Two main failure modes were observed for the units tested so far: splitting failure of the lap splices and rebar rupture. The first scenario occurred in all test units except LAP-P10, an example of which is shown in Figures 5a and 5b (for test unit LAP-P16). As it can be seen, this failure mode is triggered by the formation of vertical cracks developing along the entire lap splice length. Relative slip of spliced rebars occurs, thus limiting the transfer of forces, and reducing the load carrying capacity of the specimen. On the other hand, when lap splices are long and well confined as in LAP-P10, the deformations concentrate in the horizontal crack above the lap splice (see Figure 5c). Horizontal and vertical cracks within the spliced region remained small in width. Additionally, the latter did not develop along the entire splice length. Before failure, the width of the crack above the spliced region reached about 20 mm and, upon load reversal, significant buckling of the bars anchored at the top RC block occurred in compression producing micro-cracks at the convex rebar side. The same bars then fractured in tension causing the loss of load capacity of the specimen (Figure 5d).

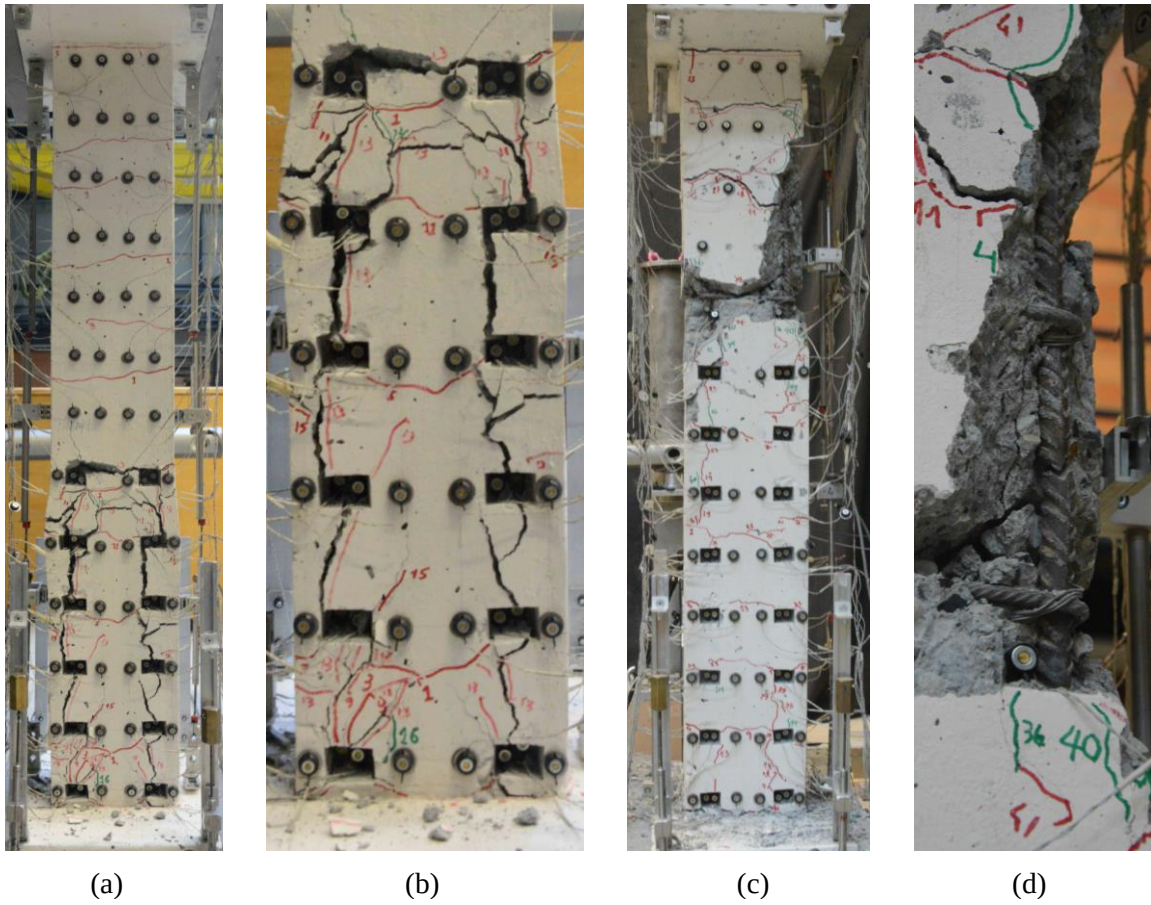


Figure 5. (a) Splitting failure of test unit LAP-P16; (b) Close-up of the lap splice region at failure; (c) Failure due to rebar rupture above the splice region of test unit LAP-P10; (d) Close-up of the bar failure.

3.3 Influence of confining reinforcement on the lap splice ductility capacity

As shown in Figure 4b, confining reinforcement ratio and ductility capacity of lap splices appear to be positively correlated. For the same test units, Figure 6 displays the lap splice strains ε_{ls} at the onset of specimen failure; this quantity is computed as the relative displacement between the LEDs immediately above and below the lap splice region divided by their initial base length. In Figure 6a those strains are plotted separately for each lap splice while in Figure 6b, for each test unit, the minimum ε_{ls} is reported as function of the confining reinforcement ratio ρ_w . Up to the onset of splice failure, the strains recorded in the four splices of the same specimen are consistent among them as the difference between the maximum and minimum ε_{ls} never exceeds 20%. Moreover, the minimum ε_{ls} at failure onset increases with the amount of provided confining reinforcement and, for the considered value of lap splice length ($l_s=40\phi$), the relation appears to acceptably fit a linear trend. The latter is

being further investigated, namely its dependence on the splice length.

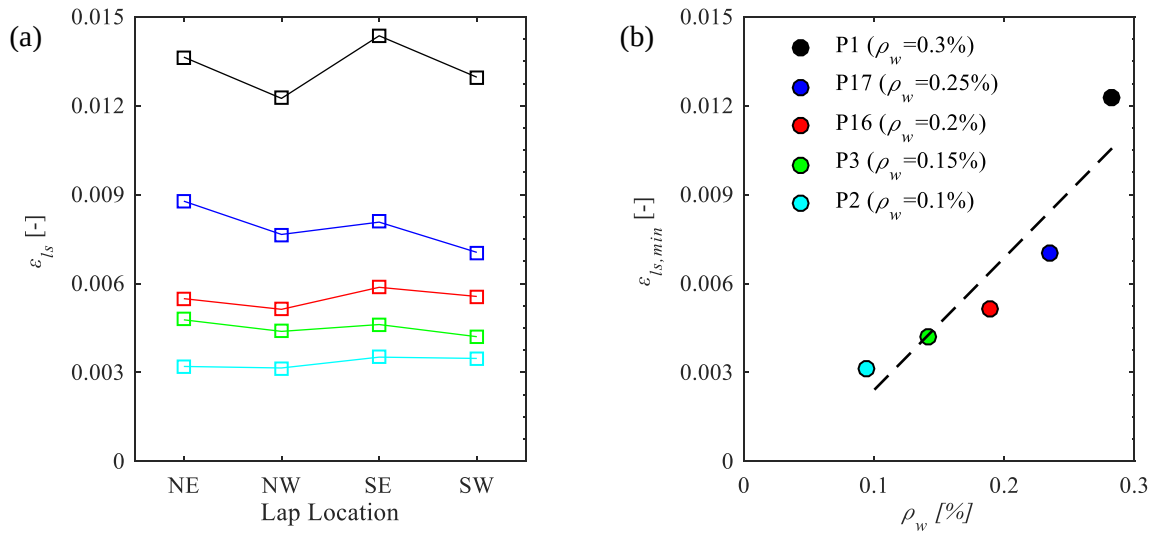


Figure 6. (a) Individual lap splice strain at degradation onset; (b) Minimum lap splice strain at degradation onset.

4. CONCLUSIONS

Lap splices located in the plastic hinge region of RC walls/piers may lead to a reduction of both their strength and displacement capacity. The detailing of the spliced region is fundamental to ensure a sufficiently ductile behaviour of the structural member.

This paper presents the first report on an ongoing experimental programme on 24 RC wall/pier boundary elements tested under tension-compression cyclic loads. Lap splice length, confining reinforcement and loading history are considered as test parameters. The specimens are instrumented with LVDTs and LED grids, which enable the computation of strains along the splices. Within this region, LEDs are also glued directly onto the rebars, allowing for the determination of relative bar-bar and concrete-bar slips.

Preliminary results on the first nine units tested showed the following:

- (i) The displacement capacity of lap splices increases with both splice length l_s and confining reinforcement ρ_w .
- (ii) Degradation due to cyclic loading history contributes to reduce the ductility capacity of the spliced member.
- (iii) Two main failure modes are observed: splitting failure along the lap splices and rebar rupture at the crack above the spliced region. This second failure mode occurred only for the specimen featuring the longest and most confined lap splices (LAP-P10 with $l_s=60\phi_l$ and $\rho_w=0.3\%$).
- (iv) For a splice length $l_s=40\phi_l$, an approximately linear relationship between splice strain at degradation onset and confining reinforcement ratio appears to fit well the experimental results.

5. ACKNOWLEDGMENTS

The financial support by the Swiss Federal Roads Office (FEDRO) to the project number AGB 2015/002, under which the present study is carried out, is acknowledged. Moreover, the authors would like to thank Tiago Nico Pereira for the precious help in the laboratory and Massimo Fermani for the assistance in creating some figures.

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