DATA PAPER

Uniaxial Cyclic Tests on Reinforced Concrete Members with Lap Splices

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This data paper presents the quasi-static uniaxial cyclic tests of 24 reinforced concrete members, of which 22 feature lap splices and 2 are reference units with continuous reinforcement. The objective of the experimental program is to investigate the influence of lap splice length ($l_s$), confining reinforcement, and loading history on the behavior of lap splices. Particular attention is placed on the measurement of local deformation quantities, such as lap splice strains and rebar-concrete slip. Details of the geometry and reinforcement layout of the specimens as well as the employed test setup, instrumentation, and loading protocols are provided. The global behavior of the test units, including the observed crack pattern and failure modes, are discussed. The organization of the experimental data, which are made available for public use under DOI: 10.5281/zenodo.1205887, is outlined in detail. [DOI: 10.1193/041418EQS091DP]

INTRODUCTION

The strength and ductility capacity of reinforced concrete (RC) members may be considerably reduced by the presence of lap splices, particularly if located in regions where the inelastic deformations are largest, such as plastic hinges. Several experimental programs can be found in the literature on spliced RC members, the majority of which are aimed at investigating the lap splice strength under monotonic (e.g., Chinn et al. 1955, Tepfers 1973) and cyclic (e.g., Gergely and White 1980, Lukose et al. 1982) loading. A complete review of past experimental tests is beyond the scope of this document, and the reader is referred to Almeida et al. (2017). Research on the displacement capacity of lap splices is instead scarcer, and it was only recently addressed by Biskinis and Fardis (2010), Hannewald (2013), and Tarquini et al. (2017), who proposed limit strains defining the lap splice failure. However, the latter were based on semiempirical approaches or limited experimental databases of members subjected to flexural loads wherein only global displacements were typically measured. Therefore, broader and more detailed test data are required to better characterize the full hysteretic response of lap splices as a function of the main influencing parameters.

This paper presents quasi-static tension-compression cyclic tests on 24 half-scale RC wall boundary elements carried out at the Earthquake Engineering and Structural Dynamics (EESD) Laboratory of the École Polytechnique Fédérale de Lausanne (EPFL). The test
units (TUs), of which 22 had lap splices and 2 were reference units with continuous reinforcement, were designed based on the RC walls tested by Bimschas (2010) and Hannewald (2013). Details of the prototype structure, which represents a typical Swiss bridge pier, as well as the scaling procedure can be found in Bimschas (2010). The tests of the boundary elements have as objectives to study the influence of lap splice length ($l_s$), confining reinforcement, and loading history (LH) on the behavior of lap splices. These parameters were singled out by Almeida et al. (2017) and Tarquini et al. (2017) as those that influence the ductility of spliced RC walls most.

The document is organized as follows: the geometry of the TUs, the reinforcement layout, and the mechanical features of the employed materials are first introduced. The test setup, loading protocol, and utilized instrumentation are then described. Next, the behavior of the specimens in terms of crack patterns and failure modes is addressed. A section is dedicated to the organization of the raw and postprocessed test data, which are shared online and free to download. Finally, a few example plots that can be obtained from the processed experimental data are provided.

**DESCRIPTION OF TEST UNITS**

**GEOMETRY AND REINFORCEMENT LAYOUT**

The entire set of TUs is listed in Table 1 together with the main geometrical and reinforcement layout characteristics. As an example, a three-dimensional (3-D) representation as well as the vertical and cross-sectional views of specimen LAP-P1 are displayed in Figure 1.

All TUs share the same geometry with a column height $h = 1,260$ mm and a square cross section with side dimension $b = 200$ mm. A $550 \times 550 \times 310$-mm foundation and top beam were cast at the member extremities to allow for the anchorage of the longitudinal rebars and clamp the specimens to the testing machine.

The longitudinal reinforcement was composed of four diameter ($\Omega_l$) 14-mm rebars which, in 22 of the 24 TUs [identified with the label LAP-P(i) in Table 1], were spliced above the column-foundation interface. The top-anchored rebar was always placed on the outside with respect to the one anchored to the foundation—see Figure 1d. The lap splice length was a variable parameter of the experimental program and ranged from 25 to 60 times the longitudinal rebar diameter $\Omega_l$. Two TUs featured continuous reinforcement and were labeled LAP-C(i). Transverse (confining) reinforcement was provided by $\Omega 6$-mm hoops with 90-degree hooks, as representative of 1960s and 1970s central European construction practice (Figure 1d). The confining reinforcement ratio ($\rho_t$) was the second variable parameter of the test program and was bounded between 0% and 0.3%. Both ranges of $l_s$ and $\rho_t$ were defined in order to investigate preseismic (Melek and Wallace 2004, Elnady 2008) as well as code-compliant [European Committee for Standardization 2004; Swiss Society of Engineers and Architects (SIA) 2004] detailing configurations. A clear concrete cover $c = 20$ mm, measured from the outer edge of the stirrups, was adopted.

For instrumentation purposes, specifically designed plastic pieces, removed after casting, were used to create $20 \times 30$-mm holes in the concrete cover and to allow the spliced...
bars to be visible at predefined locations. More details on the dimensions and locations
of these constructive details can be found in the “Optical Triangulation Measurements”
subsection.

**MATERIAL PROPERTIES**

The TUs were cast horizontally, four at a time. Concrete strength was assessed for each
casting series by testing three 160 × 320-mm concrete cylinders according to SIA (1989).
The average concrete cylinder strength \( f'_c \) and units of the corresponding batch are
displayed in Table 2.

All the rebars composing the longitudinal reinforcement \( \varnothing_l = 14 \text{ mm} \) were obtained
from the same production batch as well as those used for the transverse reinforcement
\( \varnothing_t = 6 \text{ mm} \). The main steel properties were derived from uniaxial tension tests (SIA
1989) and are reported in Table 3; it is noted that, differently from the hot-rolled steel

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**Table 1.** Main geometrical features and reinforcement details of the specimens

| Label | \( h \) (mm) | \( b \) (mm) | \( l_s \) (mm) | \( A_l(\rho_l) \) (mm) | \( A_t(\rho_t) \) (mm) | LH |
|-------|--------------|--------------|--------------|-----------------|-----------------|----|
| LAP-P1 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@100 (∼0.3%) | C1 |
| LAP-P2 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@300 (∼0.1%) | C1 |
| LAP-P3 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C1 |
| LAP-P4 | 1,260 | 200 | 350 (25 Ø) | 4 × Ø14 (∼1.5%) | Ø6@100 (∼0.3%) | C1 |
| LAP-P5 | 1,260 | 200 | 840 (60 Ø) | 4 × Ø14 (∼1.5%) | Ø6@300 (∼0.1%) | C1 |
| LAP-P6 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | M |
| LAP-P7 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C1 |
| LAP-P8 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | M |
| LAP-P9 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C2 |
| LAP-P10 | 1,260 | 200 | 840 (60 Ø) | 4 × Ø14 (∼1.5%) | Ø6@100 (∼0.3%) | C1 |
| LAP-P11 | 1,260 | 200 | 350 (25 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C1 |
| LAP-P12 | 1,260 | 200 | 350 (25 Ø) | 4 × Ø14 (∼1.5%) | Ø6@300 (∼0.1%) | C1 |
| LAP-P13 | 1,260 | 200 | 840 (60 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C1 |
| LAP-P14 | 1,260 | 200 | 840 (60 Ø) | 4 × Ø14 (∼1.5%) | – (∼0%) | C1 |
| LAP-P15 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | – (∼0%) | C1 |
| LAP-P16 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@150 (∼0.2%) | C1 |
| LAP-P17 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@120 (∼0.25%) | C1 |
| LAP-P18 | 1,260 | 200 | 700 (50 Ø) | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C1 |
| LAP-P19 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@120 (∼0.25%) | M |
| LAP-P20 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@120 (∼0.25%) | C1 |
| LAP-P21 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@120 (∼0.25%) | C3 |
| LAP-P22 | 1,260 | 200 | 560 (40 Ø) | 4 × Ø14 (∼1.5%) | Ø6@120 (∼0.25%) | C4 |
| LAP-C1 | 1,260 | 200 | – | 4 × Ø14 (∼1.5%) | Ø6@200 (∼0.15%) | C1 |
| LAP-C2 | 1,260 | 200 | – | 4 × Ø14 (∼1.5%) | Ø6@100 (∼0.3%) | C1 |

Note: \( h \), specimen height; \( b \), cross section width; \( l_s \), lap splice length; \( \varnothing_l \), longitudinal bar diameter; \( A_l \), longitudinal reinforcement content; \( \rho_l \), longitudinal reinforcement ratio; \( A_t \), confining reinforcement content; \( \rho_t \), confining reinforcement ratio.
used for the longitudinal reinforcement, the cold-formed transverse steel did not present any yield plateau. The test results as well as the full steel stress-strain curves are part of the shared data, as discussed in the section “Organization of Test Data.”

Table 2. Mean concrete cylinder strength

| TU LAP- | P1, P2, P3, C1 | P4, P5, P7, P9 | P6, P8, P10, C2 | P11, P12, P13, P14 | P15, P16, P17, P18 | P19, P20, P21, P22 |
|---------|--------------|---------------|---------------|-------------------|-------------------|-------------------|
| $f'_c$ (MPa) | 31.7 | 30.4 | 31.6 | 33.1 | 34.4 | 33.5 |

Note: $f'_c$, concrete cylinder compressive strength was determined from three tests per casting series.

Table 3. Mechanical characterization of the reinforcing bars (average of six tests per diameter)

| Reinforcement | $f_y$ (MPa) | $f_u$ (MPa) | $\varepsilon_y$ (%) | $\varepsilon_h$ (%) | $\varepsilon_u$ (%) |
|---------------|-------------|-------------|---------------------|---------------------|---------------------|
| Longitudinal (Ø14 mm) | 510 | 635 | 0.25 | 0.95 | 9.3 |
| Transverse (Ø6 mm) | 475 | 625 | 0.25 | 0.25 | 9.8 |

Note: $f_y$, steel yield strength; $f_u$, steel ultimate tensile strength; $\varepsilon_y$, steel yield strain; $\varepsilon_h$, steel strain at hardening onset; $\varepsilon_u$, steel strain at ultimate strength.
TEST SETUP, LOADING PROTOCOL, AND INSTRUMENTATION

TEST SETUP

The test setup used for all the specimens is depicted in Figure 2. The TUs are clamped at both the foundation and top beam level to two T-shaped steel profiles. The latter are in turn prestressed to the testing machine, which is composed of a mobile bottom hydraulic piston and fixed top. The actuator has a capacity of 2.5 MN in tension and 10 MN in compression and a stroke of 250 mm.

LOADING PROTOCOL

The tests were performed under quasi-static loading conditions and displacement control. Five different protocols, including four cyclic and one monotonic, were defined to investigate the impact of LH on the behavior of lap splices. The four cyclic loading protocols differed with regard to the ratio of tension and compression displacements that were applied within one cycle. This ratio was chosen as a test parameter because damage inferred by compression strains can affect the force-displacement response of lap splices under tension. The various loading protocols are described in the following section. The protocol that was applied to each TU is reported in the LH column of Table 1.

- Reference cyclic LH (C1): It consists of the application of increasing vertical displacements ($\Delta_v$) with a 10:1 ratio between tension and compression. This ratio was determined based on the strain proportion observed along the lap splice region of the walls tested by Bimschas (2010) and Hannewald et al. (2013) at the onset of splice failure.

Figure 2. Test setup: (a) computer-aided design rendering; (b) bird’s-eye view.
Each peak displacement is referred to as a load step (LS); a cycle is composed of two LS (tension and compression) and two cycles are performed at each displacement amplitude, as shown in Figure 3a. Average vertical strains ($\varepsilon_v$) obtained as the ratio of the applied vertical displacements ($\Delta_v$) and specimen height ($h$) are indicated on the right y-axis. After the first three displacement levels at $\Delta_v = 1, 2, \text{ and } 3 \text{ mm (}$ $\varepsilon_v \approx 0.08\%, 0.16\%, \text{ and } 0.24\%)$, which correspond to the preyield phase, 3-mm increments were considered for the following amplitudes until specimen failure: $\Delta_v = 6, 9, 12 \text{ mm... or } \varepsilon_v \approx 0.48\%, 0.71\%, 0.95\%$. The latter is defined to occur when the structural member has lost more than 20% of its maximum recorded axial force, either in tension or compression. The test is then concluded with a final pulling cycle until a large level of displacement is deemed close to compromising the member integrity.

- Double compression LH (C2): Similar to the reference protocol (C1) except that the imposed compression levels were twice as large, i.e., tension to compression ratio of 10:2; see Figure 3b.
- Repeated cyclic LH (C3): No negative displacements are applied. On each LS following a tensile displacement, the TUs are unloaded to zero displacement; see Figure 3c.
- Fixed high compression force LH (C4): A value of approximately 90% of the axial load ratio ($ALR = N/f_c' \cdot A_g$) is applied at each compression LS; see Figure 3d.
- Tensile monotonic LH (M): The column is subjected to a monotonically increasing tensile displacement until failure of the four lap splices.

Figure 3. Cyclic loading protocols used in the experimental program: (a) reference cyclic-C1; (b) double compression-C2; (c) repeated cyclic-C3; (d) fixed high compression force-C4.
It should be pointed out that the actual applied protocols slightly differed from the intended ones described, as the actuator was stopped manually at each LS. The real displacement history imposed during each test is reported in the individual TU reports that are discussed in the section “Organization of Test Data.”

**INSTRUMENTATION**

The TUs were instrumented using conventional measurements and optical triangulation systems. Crack widths were measured manually. Moreover, at each LS, photos were taken and videos were recorded.

**Conventional Measurements**

The same conventional instrumentation was used in all the tests of the experimental program. A total of 33 channels were recorded with the available data acquisition software (Hottinger Baldwin Messtechnik GmbH 2000), of which 18 were directly measured and 15 computed. Displacements were evaluated by means of linear variable differential transformers (LVDTs), while load cells were employed to monitor forces.

Four LVDTs (100-mm stroke) were installed with a plumb line system at the column corners from the top beam to the foundation interface; see Figure 4a and 4b. They were used to pilot the testing machine as they indicated the applied net column deformation.

Figure 4. Instrumentation installed on the TU: (a) sketch of the LVDT pattern and close-up of the plumb line LVDT system; (b) photo of the prior-to-test east face of LAP-P1; (c) LED distribution for specimens with a lap splice length of \( l_s = 400 \); (d) photo of the prior-to-test north face of LAP-P1.
Three LVDTs in series (with different strokes) were also placed on both the east and west specimen faces, as shown in Figure 4a and 4b. Their base lengths varied from test to test with the main objective of having a backup measure of the strains in the lap splice region besides the one obtainable from the optical triangulation system discussed as follows. A supplementary LVDT was connected to the bottom mobile actuator of the testing machine to monitor that the deformations caused by the test setup remained relatively small. Four load cells to measure the axial force, with a total capacity of ±2,000 kN, were located below the fixed top of the testing machine, as depicted in Figure 2a. Additionally, an internal load cell back-calculated the imposed force from the hydraulic pressure of the machine actuator. Detailed information on the conventional measurements can be found in the individual TU reports, as discussed in the section “Organization of Test Data.”

Optical Triangulation Measurements

The north and south column faces were instrumented with a dense mesh of light-emitting diodes (LEDs). The 3-D displacement of each LED was tracked by two cameras, one per TU side, and each featuring three digital optical sensors. The hardware and software provided by the commercial system Northern Digital Inc. (NDI) Optotrak Certus HD (NDI 2009) was used.

The LED mesh on the column concrete surfaces was designed as a function of the lap splice length; it was therefore unit-specific, but it normally followed gridlines spaced 100 mm in the vertical and 50 mm in the horizontal direction, as shown in Figure 4c and 4d. Furthermore, LED pairs were also glued at a regular vertical spacing of 100 mm to the spliced adjacent rebars in the concrete holes left during the casting phase, as depicted in the close-up of Figure 4c. Such disposition permitted tracking of the relative slip between the spliced bars as well as between each bar and the surrounding concrete. Finally, on both the north and south sides, two LED rows were attached to the foundation and top beam, and single markers were glued on the steel profiles.

The LED data were recorded during loading and, for a short time period, at each LS. The latter aimed at registering stable (constant) values of the imposed vertical displacements. In the data postprocessing phase, the initial random numbering of the LEDs was ordered, and their coordinates were transformed to the following spatial reference system: the x- and z-axes refer to the horizontal directions (positive from east to west and north to south, respectively), while the y-axis refers to the vertical direction (positive from bottom to top). The origin of the coordinate system is defined as the LED located at the column in the northeast bottom corner; see Figure 4c. The specific LED grid for each TU and their numbering upon postprocessing can be found in the individual test reports; see the section “Organization of Test Data.”

Crack Widths, Photos, and Videos

Crack widths were measured by means of crack-width meters at different locations along the specimen height and for most tensile LS. They were successively recorded in the specific TU lab books, which are part of the publicly available material (refer to the section “Organization of Test Data” for more details). Photos were taken at several LS and always when a new tensile displacement level was attained. On such occasions, one photo was taken per column side as well as photos of relevant signs of damage (horizontal
and splitting cracks, concrete crushing, spalling, rebar buckling and rupture, etc.). Finally, videos were recorded during all loading phases (i.e., between successive LS) on the north and south column faces. Only for monotonic tests were videos taken on all four unit sides.

**TEST OBSERVATIONS**

This section summarizes the behavior of all the TUs. The pre-failure phase and observed failure modes are addressed in the next two subsections. Specimen-specific observations are reported in Table 4. Force-displacement responses are shown in Figures 5 and 6, where the vertical axial force \( N \) is given on the \( y \)-axis and the vertical displacement \( (\Delta_y) \) and average strain \((\varepsilon_y)\) are reported on the bottom and top \( x \)-axes, respectively. The vertical

| Specific comments | FM |
|------------------|----|
| LAP-P1: At the first cycle to \( \Delta_y = 24 \text{ mm} \ (\varepsilon_y \approx 1.9\%) \), a clear relative slip between the spliced bars on the east side (NE and SE corners) of the column was observed. During the second cycle to the same amplitude, at \( \Delta_y \approx 16 \text{ mm} \ (\varepsilon_y \approx 1.3\%) \), splitting-unzipping failure of these splices occurred with a loss of almost 35\% of the column load-carrying capacity. The third lap splice (NW corner) failed during the last cycle at \( \Delta_y \approx 18 \text{ mm} \ (\varepsilon_y \approx 1.4\%) \), according to the same failure mode. Finally, rebar rupture occurred for the top-anchored bar of the SW corner lap splice at \( \Delta_y \approx 32 \text{ mm} \ (\varepsilon_y \approx 2.5\%) \). The rupture took place above the lap splice, where the largest crack was located | M |
| LAP-P2: While loading to \( \Delta_y = 6 \text{ mm} \), upon rebar yielding \( (\Delta_y \approx 4.5 \text{ mm} , \varepsilon_y \approx 0.36\%) \), splitting-unzipping failure of the two splices on the west side occurred. A force drop of around 30\% was observed. The remaining two splices failed simultaneously during the last cycle at an applied displacement of \( \Delta_y \approx 10 \text{ mm} \ (\varepsilon_y \approx 0.8\%) \), according to a splitting-explosive failure mode | M |
| LAP-P3: The lap splice on the NE corner failed (splitting-unzipping) during the first loading to \( \Delta_y = 9 \text{ mm} \) at an applied displacement \( \Delta_y \approx 7.5 \text{ mm} \ (\varepsilon_y \approx 0.6\%) \). A strength loss of 10\% was recorded. The same failure mode was observed for the remaining lap splices: NW and SE corners failed simultaneously at \( \Delta_y \approx 9 \text{ mm} \ (\varepsilon_y \approx 0.7\%) \) on the first cycle to \( \Delta_y = 12 \text{ mm} \). At this stage, the column resisting force was reduced by 50\%. The last lap splice (SW) failed at \( \Delta_y \approx 19 \text{ mm} \ (\varepsilon_y \approx 1.5\%) \) | S-U |
| LAP-P4: Simultaneous splitting-unzipping failure of the four lap splices occurred during the first loading to \( \Delta_y = 6 \text{ mm} \) at an applied displacement \( \Delta_y \approx 4 \text{ mm} \ (\varepsilon_y \approx 0.3\%) \), corresponding to the onset of rebar yielding. The residual axial force was \( N \approx 50 \text{kN} \), approximately 15\% of the column yielding force \( N_y \) | S-U |
| LAP-P5: On the first cycle to \( \Delta_y = 18 \text{ mm} \), splitting-unzipping failure of the NE corner splice occurred at a displacement \( \Delta_y \approx 17 \text{ mm} \ (\varepsilon_y \approx 1.35\%) \). A drop of 15\% of axial force was observed. Upon load reversal, buckling of the bars above the NE and SE lap splice region took place. At the second cycle to \( \Delta_y = 18 \text{ mm} \), the resisting axial force \( N \) was around 75\% of the peak strength. On the last tensile cycle, the SE splice failed at \( \Delta_y \approx 20 \text{ mm} \ (\varepsilon_y \approx 1.6\%) \), again according to a splitting-unzipping failure type. Both the splices on the west column side showed instead a splitting-explosive failure occurring at \( \Delta_y \approx 35 \text{ mm} \ (\varepsilon_y \approx 2.8\%) \) | M |

(continued)
LAP-P6: The two lap splices on the west column side failed at an applied displacement level $\Delta_v \approx 4.5\, \text{mm}$ ($\epsilon_v \approx 0.36\%$) immediately after rebar yielding. The lap splices located on the SE and NE column corners failed at $\Delta_v \approx 9\, \text{mm}$ ($\epsilon_v \approx 0.7\%$) and $\Delta_v \approx 15\, \text{mm}$ ($\epsilon_v \approx 1.2\%$), respectively.

LAP-P7: Both splices on the west column side failed after rebar yielding ($\Delta_v \approx 4.5\, \text{mm}$, $\epsilon_v \approx 0.36\%$) while loading to $\Delta_v = 6\, \text{mm}$. A force drop of around 20%–25% was observed. The two splices on the east side failed simultaneously at $\Delta_v \approx 7.5\, \text{mm}$ ($\epsilon_v \approx 0.6\%$)

LAP-P8: Splitting-unzipping failure of the two splices on the west side occurred at a displacement level $\Delta_v \approx 12\, \text{mm}$ ($\epsilon_v \approx 0.95\%$). The same failure mode was observed for the splices on the SE and NE column corners, which failed at $\Delta_v \approx 15$ ($\epsilon_v \approx 1.2\%$) and $\Delta_v \approx 18\, \text{mm}$ ($\epsilon_v \approx 1.4\%$), respectively.

LAP-P9: Behavior similar to specimen LAP-P7. The two splices on the west column side failed at a displacement level of $\Delta_v \approx 4\, \text{mm}$ ($\epsilon_v \approx 0.3\%$) while those on the east side failed at $\Delta_v \approx 10\, \text{mm}$ ($\epsilon_v \approx 0.8\%$).

LAP-P10: Deformations concentrated on the horizontal crack located around the splice top. At displacement level $\Delta_v = -2.4\, \text{mm}$ ($\epsilon_v \approx -0.19\%$), concrete spalling was observed in the same region, promoting rebar bucking in the following compression cycles. The maximum tension displacement attained prior to first observation of reinforcement buckling was $\Delta_v = 24\, \text{mm}$ ($\epsilon_v \approx 1.9\%$). Concrete core crushing occurred on the first cycle to $\Delta_v = -2.7\, \text{mm}$ ($\epsilon_v \approx -0.21\%$) with a reduction of the compression load capacity of almost 75%. On the second loading cycle to $\Delta_v = 27\, \text{mm}$ ($\epsilon_v \approx 2.15\%$), the NW top-anchored bar fractured where it had previously buckled. Similarly, the NE top-anchored bar ruptured on the final cycle at an applied displacement $\Delta_v \approx 20\, \text{mm}$ ($\epsilon_v \approx 1.6\%$)

LAP-P11: Splitting-unzipping failure of the four lap splices occurred simultaneously before reaching rebar yielding during the first cycle to $\Delta_v = 6\, \text{mm}$. Maximum vertical force $N = 260\, \text{kN}$ was attained at imposed displacement of $\Delta_v \approx 3.5\, \text{mm}$ ($\epsilon_v \approx 0.28\%$), corresponding to 80% of the column yielding force ($N_y \approx 320\, \text{kN}$). The final residual force was $N \approx 80\, \text{kN}$.

LAP-P12: Similar behavior to LAP-P11. Failure occurred before rebar yielding at displacement $\Delta_v \approx 3.5\, \text{mm}$ ($\epsilon_v \approx 0.28\%$) and force $N = 260\, \text{kN}$. The residual force was $N \approx 80\, \text{kN}$.

LAP-P13: Similar behavior to LAP-P10. Rebar buckling was first observed at a level of compression of $\Delta_v = -1.8\, \text{mm}$ ($\epsilon_v \approx -0.14\%$); the last tension displacement prior to first observation of reinforcement buckling was $\Delta_v = 15\, \text{mm}$ ($\epsilon_v \approx 1.2\%$). Concrete crushing occurred at the first cycle to $\Delta_v = -2.1\, \text{mm}$ ($\epsilon_v \approx -0.17\%$) with a drop of force of roughly 75%. On the last tensile cycle, the NE and SW top-anchored bars fractured at the buckling locations (above the lap splice region) at $\Delta_v \approx 32\, \text{mm}$ ($\epsilon_v \approx 2.5\%$) and $\Delta_v \approx 35\, \text{mm}$ ($\epsilon_v \approx 2.8\%$), respectively. At this same displacement level, a splitting-explosive failure mode was instead observed for the SE lap splice.

LAP-P14: Before reaching $\Delta_v = 9\, \text{mm}$ ($\epsilon_v \approx 0.7\%$), the SE corner splice failed with a loud noise. A loss of force capacity of about 20% was observed. During the cycles at the amplitude level $\Delta_v = 12\, \text{mm}$, vertical cracking extended in the three remaining splices. They failed during the final cycle at $\Delta_v \approx 10\, \text{mm}$ ($\epsilon_v \approx 0.8\%$) and $\Delta_v \approx 17\, \text{mm}$ ($\epsilon_v \approx 1.35\%$) for the SW and both north face splices, respectively. At the end, the specimen showed no tensile residual force capacity.

(continued)
Table 4. (continued)

| Specific comments | FM |
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LAP-P15: All splices failed according to a splitting-explosive failure mode. The lap splices on the east side of the column failed before reaching $\Delta_v \approx 6$ mm ($\varepsilon_v \approx 0.48\%$) on the first loading to such displacement amplitude. The SW and NW lap splices failed on the final cycle at $\Delta_v \approx 9$ mm ($\varepsilon_v \approx 0.7\%$) and $\Delta_v \approx 13$ mm ($\varepsilon_v \approx 1\%$). The test concluded with no residual tensile force

LAP-P16: Splitting-unzipping failure of the east side splices occurred on the first loading to $\Delta_v = 12$ mm at $\Delta_v \approx 9$ mm ($\varepsilon_v \approx 0.7\%$). A strength loss of almost 30% was observed. The splices on the west side failed at $\Delta_v \approx 13$ mm ($\varepsilon_v \approx 1\%$) during the last loading cycle

LAP-P17: The NE corner splice failed while loading to $\Delta_v = 15$ mm ($\varepsilon_v \approx 1.2\%$) shortly before reaching the target displacement. The SE splice failed during the second cycle at the same amplitude. The splices located on the west column side failed on the last tensile cycle, again approximately at $\Delta_v \approx 15$ mm

LAP-P18: Splitting-unzipping failure of both SW and NW splices occurred during the first loading to $\Delta_v = 18$ mm at $\Delta_v \approx 13$ mm ($\varepsilon_v \approx 1\%$) and $\Delta_v \approx 15$ mm ($\varepsilon_v \approx 1.2\%$), respectively. The remaining two splices failed on the last tensile cycle at $\Delta_v \approx 30$ mm ($\varepsilon_v \approx 2.4\%$); Splitting-unzipping failure of the NE lap splice shortly preceded the splitting-explosive failure of the NW one

LAP-P19: The lap splices on the NE, SE, and NW column corners exhibited a splitting-unzipping type of failure at $\Delta_v \approx 12$ mm ($\varepsilon_v \approx 0.95\%$), $\Delta_v \approx 17$ mm ($\varepsilon_v \approx 1.35\%$), and $\Delta_v \approx 22$ mm ($\varepsilon_v \approx 1.75\%$). On the other hand, the top-beam anchored rebar of the SW corner splice ruptured at $\Delta_v \approx 50$ mm ($\varepsilon_v \approx 4\%$

LAP-P20: The first lap splice (SW corner) failed at $\Delta_v \approx 12$ mm ($\varepsilon_v \approx 0.95\%$) on the second cycle to this amplitude. The NW splice failed at the first loading to $\Delta_v = 15$ mm ($\varepsilon_v \approx 1\%$). The NE and SE corner splices failed at the last tensile cycle at $\Delta_v \approx 20$ mm ($\varepsilon_v \approx 1.6\%$) and $\Delta_v \approx 35$ mm ($\varepsilon_v \approx 2.8\%$

LAP-P21: Splitting failure of both east side splices occurred on the second cycle to $\Delta_v = 21$ mm ($\varepsilon_v \approx 1.7\%$) just before the target displacement. The NW splice failed during the last cycle at $\Delta_v \approx 28$ mm ($\varepsilon_v \approx 2.2\%$), while the SW top-anchored bar fractured at about $\Delta_v \approx 40$ mm ($\varepsilon_v \approx 3.2\%$

LAP-P22: The SE corner splice failed right before reaching $\Delta_v = 6$ mm ($\varepsilon_v \approx 0.48\%$) on the first cycle to this displacement amplitude. The NE corner splice failed on the first cycle to $\Delta_v = 12$ mm at a displacement of $\Delta_v \approx 9.5$ mm ($\varepsilon_v \approx 0.75\%$). Both the west corner splices failed at around $\Delta_v \approx 12$ mm ($\varepsilon_v \approx 0.95\%$). The loading was continued until $\Delta_v \approx 20$ mm ($\varepsilon_v \approx 1.6\%$); the residual force was around 80 kN

LAP-C1: Core concrete crushing occurred while loading to $\Delta_v = -4.2$ mm ($\varepsilon_v \approx -0.33\%$), leading to a force drop of about 85%. Spalling between the main horizontal cracks located at the center of the column had taken place on the previous cycle to $\Delta_v = -3.9$ mm ($\varepsilon_v \approx -0.31\%$), followed by rebar buckling upon load reversal. On the last tensile cycle, rupture of the SW, SE, and NW rebars was observed at the respective buckling locations for $\Delta_v \approx 35$ mm ($\varepsilon_v \approx 2.8\%$), $\Delta_v \approx 70$ mm ($\varepsilon_v \approx 5.6\%$) and $\Delta_v \approx 90$ mm ($\varepsilon_v \approx 7.1\%$

LAP-C2: Similar to the behavior of LAP-C1. Concrete crushing occurred on the first loading to $\Delta_v = -3.9$ mm ($\varepsilon_v \approx -0.31\%$) with a force loss of about 85%. On the last cycle, at approximately $\Delta_v \approx 40$ mm ($\varepsilon_v \approx 3.2\%$), the NW corner rebar ruptured at the buckling location

Note: C-C, concrete crushing followed by rebar rupture; FM, failure mode; M, mixed rebar rupture/lap splice failures; NE, northeast; NW, northwest; S-E: splitting-explosive failure of all lap splices; SE, southeast; S-U: splitting-unzipping failure of all lap splices; SW, southwest.
Figure 5. Cyclic response of specimens LAP-P1 to LAP-P12.
Figure 6. Cyclic response of specimens LAP-P13 to LAP-P22, LAP-C1, and LAP-C2.
force $N$ is computed by summing up the forces of the four load cells located below the fixed top, while $\Delta_\text{v}$ is the average displacement measured by the four plumb line LVDTs. The occurrence of splice failure, maximum tension level prior to the onset of reinforcement buckling, rebar rupture, concrete crushing, or combinations thereof are signaled by the presence of markers, while a dashed line indicates the overall specimen failure.

## PRE-FAILURE BEHAVIOR

All the specimens with lap splices behaved rather similarly until the occurrence of one of the three following events: failure of one or more lap splices, rebar rupture, or core concrete crushing. However, the strain at which failure occurred depended strongly on the TU configuration; this is shown in the next subsection. The behavior of members with continuous reinforcement was governed by a uniform crack pattern and failure in compression:

- **TUs with lap splices (LAP-P1 to LAP-P22):** Upon application of the first tensile loading ($\Delta_\text{v} = 1 \text{ mm}, \varepsilon_\text{v} \approx 0.08\%$), five to seven cracks usually formed along the column height, while two opened at the foundation and top beam interfaces. Not all cracks normally run along the entire column perimeter, particularly within the spliced region. They were spaced apart about 150 to 200 mm with an approximately constant crack width $w \approx 0.1 \text{ mm}$. Horizontal crack development (i.e., opening of the new cracks or extension and widening of existing ones) continued for the next two tensile amplitudes ($\Delta_\text{v} = 2 \text{ mm}$ and $\Delta_\text{v} = 3 \text{ mm}$). At this stage, the width ($w$) of the cracks located above and within the lap splice region started to differentiate: $w \approx 0.2 - 0.3 \text{ mm}$ for the former and $w \approx 0.1 \text{ mm}$ for the latter. At $\Delta_\text{v} = 3 \text{ mm} (\varepsilon_\text{v} \approx 0.24\%)$, the first vertical splitting cracks also appeared, although they were small and localized at the top and bottom of the splices. During compression cycles, crack closure was observed. At the first LS to $\Delta_\text{v} = 6 \text{ mm} (\varepsilon_\text{v} \approx 0.48\%)$, the TUs began to show specimen-specific behavior. Rebar yielding occurred at $\Delta_\text{v} \approx 4 \text{ mm} (\varepsilon_\text{v} \approx 0.32\%)$, after which several lap splice configurations failed (see Table 4). Only specimens LAP-P11 and LAP-P12, featuring the shortest lap splice length and medium-to-low confinement reinforcement ratios ($l_s = 25\text{Ø}, \rho_t = 0.15\%$ and 0.1%, respectively), did not reach the yield strength. For tensile displacements larger than $\Delta_\text{v} = 6 \text{ mm}$, the horizontal cracks located outside the spliced region progressively widened; on the other hand, their width remained approximately constant ($w \approx 0.1 \text{ mm}$) within the lap splice zone; see Figure 7a. The largest crack typically occurred at the top of the splices, followed by one at the foundation interface. Vertical splitting cracks extended from the bottom and top lap splice extremities toward the middle. Regarding the behavior of the TUs in compression, crack closure with no damage was observed until an average vertical strain $\varepsilon_\text{v} \approx -0.15\%$ was reached, corresponding to a total displacement $\Delta_\text{v} \approx -1.8 \text{ mm}$. At such a compression level, concrete spalling at major crack locations and development of vertical crushing cracks (usually extending pre-existing tension splitting cracks) started to take place. Whenever larger compression amplitudes were reached, extensive spalling formed above the spliced region, followed by rebar buckling and eventually crushing of the concrete core.
TUs with continuous reinforcement (LAP-C1 and LAP-C2): Unlike the units with lap splices, the crack width was approximately constant along the member height at all displacement levels. Vertical cracks formed only because of compression loading and were typically located between two horizontal cracks. Failure occurred because of concrete core crushing after buckling of longitudinal reinforcement.

OBSERVED FAILURE MODES

The occurrence of lap splice failure depended on several factors, including lap splice length, amount of confining reinforcement, LH, and location of stirrup hooks and top casting face. A thorough discussion of the influence of these parameters and a new predictive model for the strain capacity of lap splices is addressed in Tarquini et al. (2018b). Two distinct lap splice failure modes were observed: splitting-unzipping (S-U) and splitting-explosive (S-E). Both of them occurred in the opening of vertical splitting cracks along the entire splice length (see Figure 7b), which allowed the slippage of the rebars and resulted in a loss of tensile load-carrying capacity. However, in an S-U failure, vertical cracks formed gradually along the splice length; they originated at the lap splice extremities, where rebar strains are maximum, and extended toward the middle. This relatively slow pseudoductile crack-forming process was enabled by the presence of transverse reinforcement, which prevented sudden crack

Figure 7. Photos of (a) crack pattern before failure of LAP-P21, $\Delta_v = 21\text{ mm} (\varepsilon_v \approx 1.7\%)$, east face; (b) splitting-unzipping failure of LAP-P7, $\Delta_v = 15\text{ mm} (\varepsilon_v \approx 1.2\%)$, south side; (c) failure in compression of LAP-P13, $\Delta_v = -2.1\text{ mm} (\varepsilon_v \approx -0.17\%)$, south face; (d) close-up of core crushing and rebar buckling above the spliced region of LAP-P13; (e) rebar rupture after buckling, northwest top-anchored rebar, $\Delta_v = 27\text{ mm} (\varepsilon_v \approx 2.15\%)$, LAP-P10.

- TUs with continuous reinforcement (LAP-C1 and LAP-C2): Unlike the units with lap splices, the crack width was approximately constant along the member height at all displacement levels. Vertical cracks formed only because of compression loading and were typically located between two horizontal cracks. Failure occurred because of concrete core crushing after buckling of longitudinal reinforcement.
Before failure, vertical cracks typically spread along the entire lap splice length. At failure, they opened up with a nonloud, low-pitched unzipping sound, and the relative rebar slip took place. Concrete friction then became the only available force transfer mechanism; a residual force of around 20% of the rebar yield strength was typically observed. For S-E mode, no extensive vertical cracking was visible before failure, which was loud (comparable to a rebar rupture) and fragile. No residual force was available after failure.

Rebar rupture always occurred after specimen failure, i.e., after the axial force had dropped below 80% of its maximum attained value (see section “Loading Protocol”). When a specific lap splice did not fail, rupture of the top-anchored rebar took place above the spliced region where the largest crack formed; see Figure 7e. If large compression levels were reached, rebar rupture was preceded by buckling and core concrete crushing, as shown in Figure 7c and 7d. The latter was normally associated with a strength loss of around 80%.

ORGANIZATION OF TEST DATA

The test data are publicly available and free to download from the platform Zenodo at the following DOI: 10.5281/zenodo.1205887 (Tarquini et al. 2018a). The structure of the data organization is illustrated in the flowchart of Figure 8. A separate folder [e.g., LAP_C(i), LAP_P(i)] is uploaded for each TU, the content of which is described in the next subsection.

LAP_P(i)/LAP_C(i) FOLDERS

An informative file and four main folders are made available for each TU:

- **LAP_P(i)/LAP_C(i)_Specimen_description** file: These files include the unit-specific reinforcement layout, LED pattern and numbering upon postprocessing, LVDT base lengths, actual applied displacement history, and force-displacement response. Moreover, a detailed description of the measured, computed, and postprocessed conventional channels is provided.

- **01_Material_tests** folder: Two subfolders contain the results of the concrete and reinforcement material tests. A pdf file is provided for the concrete cylinder compression tests, while an xls file for each diameter is available for the steel. The latter contains the experimental data (stress-strain curves) as well as mean values of the main quantities to be used for modeling purposes. It is noted that since the reinforcement came from the same production batch for all TUs, the corresponding material test files do not change from one specimen to the other.

- **02_Experimental_level** folder: It includes the xls lab book file and two folders labeled “Photos” and “Videos.” The lab book reports the main facts relative to the tests as well as live observations on the behavior of the TUs. Other useful information can be found, such as the date and time at which every LS was performed, LVDT base lengths, nonconnected LEDs in their original numbering, and attained vertical forces (N) and displacements (Δv) at each LS. The folder “Photos” contains a selection of photos taken at different LS during the test. Where available, photos of the four column sides at the beginning of the test (LS00), at the last LS before failure, at the first LS after failure, and after significant localized damage are included.
Similarly, the folder “Videos” contains trimmed videos of the most important moments of the test, such as splice failures, rebar ruptures, or concrete crushing.

- **03_Unprocessed_data** folder: The as-recorded data belong to this folder. They were differentiated between conventional data and data obtained from the optical triangulation system. The relationship between the LS and the corresponding data files is straightforward for the conventional data, while it is reported in the lab book for the LED data. A more detailed description of the conventional data, including the definition of the different channels and their numbering, can be found in the specific specimen description file. As for the optical triangulation data, the xls files contain the recording of the 3-D displacement field of all LEDs, organized in columns. Nonconnected or nonvisible LEDs result in empty columns for the
The camera sensor settings are stored in NDI-specific-format files (nco extension). It is noted that at the unprocessed data level, the LED numbering is unorganized, and the origin of the reference system is given by the center of the master sensor. Furthermore, at this level, the LED data and the data gained from the conventional measurement system are not synchronized. The synchronization between the conventional and optical measurement systems is performed during the postprocessing of the data through the LED conventional channel, which reports when the optical system is recording (see the TU description files for more details). The LED system was therefore always switched on after the conventional system and off before the conventional system.

- **04_Postprocessed_data folder**: The data was postprocessed in order to synchronize the conventional and optical measurement systems, discard data recorded prior to or after loading, and remove any bias or data that is not linked to the behavior of the TUs (e.g., LEDs falling off). Two subfolders contain the postprocessed conventional and optical triangulation data. In the “Conventional” folder, a csv file reports the conventional data organized in 41 columns; the first 33 involve measured and computed channels, while the last 8 concern quantities added in the postprocessing phase. The correspondence between columns and channels as well as the definition of the postprocessed quantities are provided in the TU description files. The “Optical_triangulation” folder features three csv files corresponding to the x, y, and z LED coordinates after renumbering and transformation into the new reference system presented in the subsection “Optical Triangulation Measurements.” Each column corresponds to a single LED. The LED numbering after postprocessing is illustrated in the TU-specific description files.

**POSTPROCESSED DATA AND EXAMPLE PLOTS**

By using the postprocessed experimental data, several plots can be produced. As an example, the force-displacement responses of Figures 6 and 7 were obtained by using the forces $N$ and vertical displacements $\Delta v$ from the postprocessed conventional measurements (Channels 35 and 20, respectively). Global displacements can also be derived from the postprocessed optical triangulation measurements as the vertical displacement difference between markers glued on the top beam and foundation RC blocks. However, LED data may also be employed to evaluate local deformations: Figure 9a displays the force versus average lap splice strain ($\varepsilon_{ls}$) envelopes, where $\varepsilon_{ls}$ is determined using the LEDs immediately above and below the spliced region. The history of $\varepsilon_{ls}$ throughout all loading protocol is represented in Figure 9b, while the same quantity is shown in Figure 9c at four different LS. As can be observed, the strain increases for increasing applied vertical displacements, and it is rather constant between the four splices. The vertical strain distribution of LAP-P17 at the onset of lap splice failure is illustrated in Figure 9d. Note how the vertical strains are concentrated in the crack located right above the lap splice region and at the interfaces to the foundation and top beam. Moreover, the vertical strains computed within the lap splice region are smaller than those in the region above. Finally, Figure 9e and 9f depict, respectively, the axial strain of the foundation anchored rebar and the relative slip between the same rebar and concrete. Both quantities were evaluated at the LS preceding the splice failure. The slip is obtained by subtracting the displacement recorded by the markers glued on the concrete from
the adjacent LEDs glued on the rebars. As expected, both the slip and the rebar strain are larger at the bottom, where the bar is anchored and the deformations are maximum.

**SUMMARY**

Twenty-four RC members, of which 22 have lap splices and 2 are reference units with continuous reinforcement, were tested at the EESD Laboratory of EPFL. This paper presents the main features of the experimental program, including a description of the specimens, test setup, imposed loading protocols, and instrumentation. Test observations as well as the organization of the obtained data are described.
All the units featured the same geometry and were tested under uniaxial quasi-static tension-compression cyclic loading. The goal was to study the influence of splice length, confining reinforcement, and LH on the behavior of lap splices. Four different lap splice lengths ranging from 25 to 60 times the longitudinal rebar diameter were considered as well as five distinct confining reinforcement ratios from $\rho_t = 0\%$ to 0.3\%. In total, five loading protocols were imposed, four cyclic and one monotonic.

The TUs were all equipped with conventional instrumentation and an optical measurement system. The latter was composed of a fine mesh of LEDs glued on the north and south column faces, on both the concrete surface and the spliced rebars. This arrangement allowed for computing several local deformation quantities, such as concrete strains, lap splice strains, and rebar-concrete slip. The raw and processed experimental data are made publicly accessible through the Zenodo platform under DOI: 10.5281/zenodo.1205887 (Tarquini et al. 2018a).

All the spliced units behaved similarly until the onset of failure, which occurred because of the opening of vertical splitting cracks along the lap splice length. Depending on the amount of provided confining reinforcement, an S-U or S-E failure mode could be observed. The lap splice failures occurred, however, at very different strain demands, which depended on the lap splice length, confining reinforcement, and, to a lesser extent, on the LH. For very long splices that were well-confined, the splices did not fail, and rupture of the top-anchored rebar occurred. This happened after the specimen failed in compression due to core concrete crushing.

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