THE EFFECT OF LAP-SPLICE CONFIGURATION ON SEISMIC PERFORMANCE OF SUBSTANDARD RC COLUMNS

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ABSTRACT:

A considerable amount of existing reinforced concrete (RC) buildings in developing countries possess vital deficiencies such as incorporating poor quality of concrete and insufficient transverse reinforcement, and use of plain reinforcing bars without proper detailing, such as inadequate configurations of lap-splices at critical plastic hinging zones. While these can affect the strength and ductility of structural members adversely under seismic actions, research on such substandard structural members is scarce. As such, further information is valuable for the assessment of the seismic safety of such substandard columns constructed with inadequate lap-splice configurations of plain round bars. Therefore, this study aims to investigate the effects of different lap-splice configurations of plain bars on the seismic performance of substandard RC columns and contribute to the development of assessment codes for such existing substandard buildings. Towards this aim, three full-scale columns were constructed to represent typical characteristics of substandard RC columns. The columns were subjected to constant axial loading (with an axial load to capacity ratio of 0.3) and reversed cyclic displacement reversals simultaneously representing gravity loads and seismic actions, respectively. The test program included i) one reference column with continuous longitudinal bars (no lap-spliced connection), ii) one lap-spliced column with an overlap length of 20 times the longitudinal bar diameter without any hook and iii) one lap-spliced column with an overlap length of 20 times the longitudinal bar diameter with a 180-degree hook. Test results demonstrated that columns with lap-splices did not reach their flexural strength and experienced more remarkable strength degradation with respect to the column reinforced with continuous longitudinal bars. On the other hand, presence of a 180-degree hook at the ends of spliced bars reduced the negative influence of inadequate lap-splice length in terms of strength and ductility.

KEYWORDS: Column, Lap-splice, Reinforced Concrete, Seismic, Substandard

1. INTRODUCTION

In many developing countries, there are considerable amount of substandard RC structures having inadequacies in terms of complying with up-to-date design guidelines. Deficiencies such as use of low strength concrete, insufficient transverse reinforcement and plain reinforcing bars without proper construction details (ie. inadequate configurations of lap-splices) are commonly observed in these substandard structures. Understanding the behavior of such structures in the event of a possible earthquake plays an essential role for developing structural intervention approaches to avoid potential losses due to such deficiencies. In case of presence of insufficient lap-splice length in RC elements, the yield strength of the longitudinal reinforcing bar must be decreased proportionally with the ratio of existing lap splice length to the required lap splice length while calculating the section moment capacity [1-3]. The seismic behavior of RC columns with lap-splice deficiency has been the subject of many experimental and numerical studies in the last decades. The experimental studies were carried out considering different parameters (e. g., lap-splice length, cross-sectional dimensions, axial load). In most of the existing experimental studies in the literature, deformed longitudinal reinforcing bars were used in the columns with lap-splice deficiency (e.g., [4-10]). On the other side, very few experimental research were conducted about columns with plain longitudinal reinforcing bars and lap-splice deficiency (e.g., [11-14]) and many other experimental researchers investigated strengthening techniques for columns with lap-splice deficiencies (e.g., [15-19]). Furthermore, some numerical efforts were spent on lap-splice deficiencies of RC members [e.g., 20-23]. Investigating all these studies, it is revealed that there is a need to understand the behavior of low concrete strength RC columns having plain reinforcing bars and lap-splice deficiencies under seismic loads. This study aims to investigate the behavior of RC columns with plain reinforcing bars and lap-splices under constant axial load (i.e., under axial loads corresponding to 30% of their axial load capacities without considering longitudinal bars) and cyclic lateral load which is representing seismic actions. Moreover, it is aimed that the findings of the study will contribute to the development of performance assessment codes for existing substandard buildings. For this purpose, three full-scale cantilever column specimens with low concrete compression strength (12.4 MPa), inadequate transverse reinforcement and short lap-splice length (length of 20 times the longitudinal bar diameter) of different configurations were constructed and tested. In this paper, after outlining the characteristics of the specimens and the test setup, test results are discussed focusing on the hysteretic lateral load-displacement behavior and observed damage pattern.

2. EXPERIMENTAL STUDY

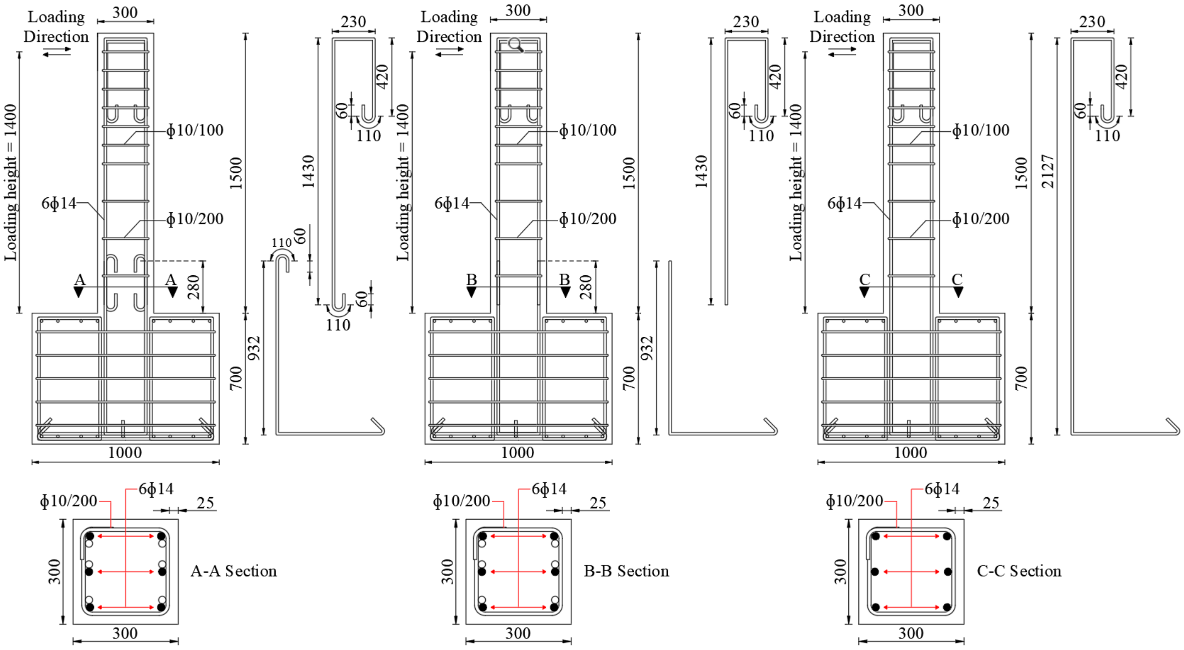
2.1. Specimens

Three full-scale cantilever column specimens with 300 mm × 300 mm cross-section and 1500 mm height were constructed. Specimens were constructed by using low compressive strength concrete and plain reinforcing bars to represent characteristics of existing columns in substandard RC structures. The average standard cylinder compressive strength at around the time of the test-days was 12.4 MPa. Mix-proportion of the concrete is presented in Table 1. Plain bars were used for both longitudinal (average yield strength of 320 MPa) and transverse reinforcement (average yield strength of 356 MPa).

Table 1 - Mix-proportion of the concrete (kg/m^3)

Aggregate No.1 (5-12 mm)	Crushed Sand (0-4 mm)	Cement	Water	Water/Cement ratio
752	1124	200	220	1.1

Six 14 mm-diameter longitudinal reinforcing bars were used with three different lap-splice configurations, i) one reference column with continuous longitudinal bars (no lap-spliced connection), ii) one lap-spliced column with an overlap length of 20 times the longitudinal bar diameter (280 mm) without any hook and iii) one lap-spliced column with an overlap length of 20 times the longitudinal bar diameter with 180-degree hooks, respectively. Longitudinal reinforcing bars were confined by 10 mm-diameter transverse reinforcements with 90° hook and a spacing of 200 mm representing common insufficient transverse reinforcement cases in substandard structures. In the specimen notation, the first abbreviation *S* denotes the specimen, whereas *H, NH, C* indicate lap-spliced specimen with 180-degree hooks, lap-spliced specimen with no hook and specimen with continuous longitudinal bars, respectively. The configurations of lap-splices, dimensions and reinforcing bar details of the specimens are presented in Figure 1.



a) b) c)

Figure 1 - The lap-splice configurations, dimensions and reinforcement details for a) SH, b) SNH and c) SC columns (all dimensions in mm)

For the lap-spliced specimens, the geometric ratio of the longitudinal bars outside and inside of the overlap zone were 1% and 2%, respectively. For the specimen with continuous longitudinal bars (SC), the geometric ratio of the longitudinal bars along the entire column was 1%. Clear concrete cover to the outer surface of transverse reinforcing bar of the specimens was 25 mm. Each specimen jointed a RC foundation block, with dimensions of 1000 × 1000 × 700 mm, which was anchored to the laboratory strong floor.

2.2. Test Setup, Instrumentation and Testing Procedure

The specimens were tested under constant axial load and reversed cyclic lateral loads applied in a displacement-controlled quasi-static manner. Reversed cyclic lateral loads were applied at the top of each specimen, at 1400 mm height from the RC member base, using a 300 kN capacity servo-controlled hydraulic actuator connected to a strong wall at the other end. Target drift ratios for reversed cyclic lateral load, calculated as the ratio of the lateral displacement at the axis of the actuator to the clear height (distance between base of the column and center of the actuator), were ±0.125, ±0.25, ±0.50, ±0.75, ±1, ±1.50, ±2, ±2.50, ±3 and ±4, in push and pull directions. Reversed displacement cycles for each target drift ratio were repeated twice according to ACI 374.2R-13 [24] loading protocol. Testing procedure was maintained until a loss of at least 25% of lateral and/or axial load capacity in any cycle compared to the previous cycle. The column axial load was applied by using a hydraulic jack placed between the top of the column and a rigid steel beam, which was connected to the strong floor with two hinges at the level of column-foundation intersection. All columns were subject to the same axial load ratios (n=0.30, where n is the axial load ratio, the ratio of the applied axial load to axial load-carrying capacity, which is calculated by $f_c A_g$ where A_g is the gross cross-sectional area of the column and f_c is the compressive strength of concrete derived from uniaxial compression tests of standard cylinders (150 mm × 300 mm)). Details of the test setup and instrumentation are illustrated in Fig. 2.

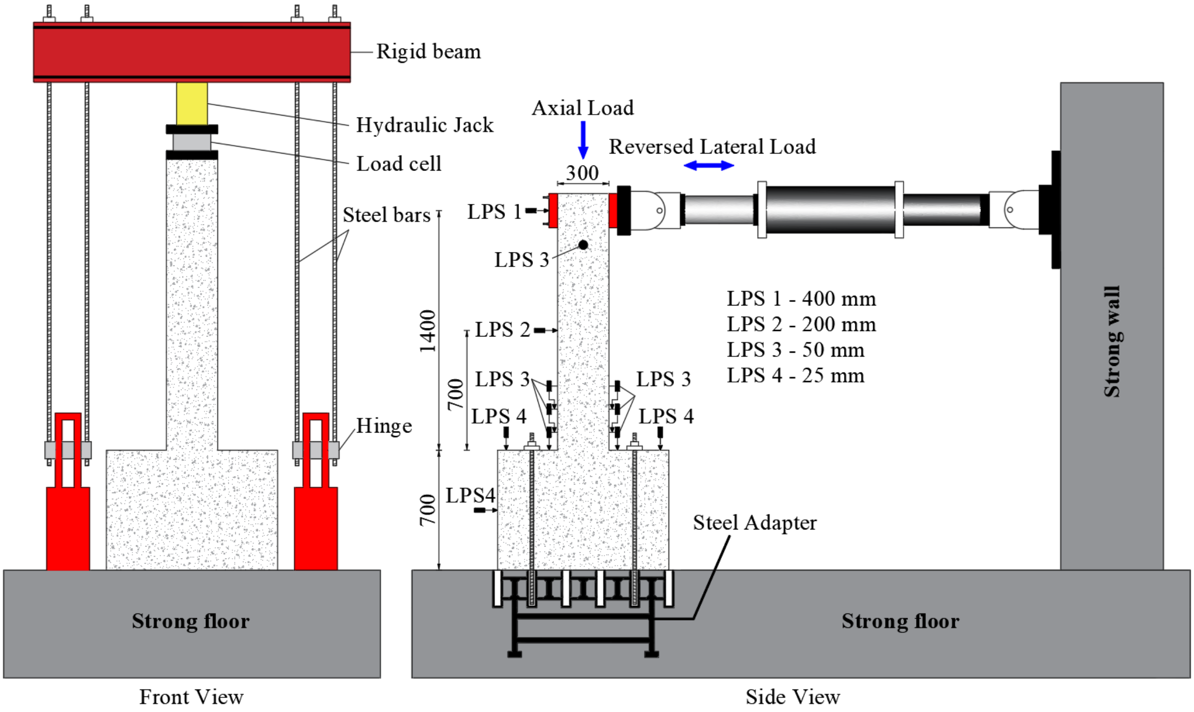


Figure 2 - Test setup and instrumentation (all dimensions in mm)

The specimens were equipped with twelve linear position sensors measuring lateral and vertical displacements as shown in Fig. 2. Two linear position sensors were instrumented horizontally at the top and mid-height of the column to measure the lateral displacement of the column. One linear position sensor was mounted horizontally at the top of the column perpendicular to the loading direction to measure the out-of-plane displacement. There was no out-of-plane displacement for any specimens. Two linear position sensors were installed vertically on the opposite corners of the footing to measure the possible rotations and one linear position sensor was placed horizontally at the mid-height of the footing to measure the lateral displacement of the footing. For all specimens, neither rotation nor lateral displacement was measured in the footing. For measuring average rotations and curvatures, six linear position sensors mounted vertically on both sides of each column along gage lengths of 30 mm, 150 mm and 300 mm from the top of the foundation which corresponds to *h/10*, *h/2* and *h*, where *h* is the depth of the column. As shown in Fig. 3, electrical resistance strain gauges were also installed on both the longitudinal and transverse reinforcing bars, for measuring steel strains. Strain distribution along both starter (denoted as S) and longitudinal (denoted as L) bars at 1.0% drift ratio for all specimens are plotted in Fig. 4. Strain distributions indicate that measured steel strains at both starter and longitudinal bars are lower than yield strain of the longitudinal bars (0.002).

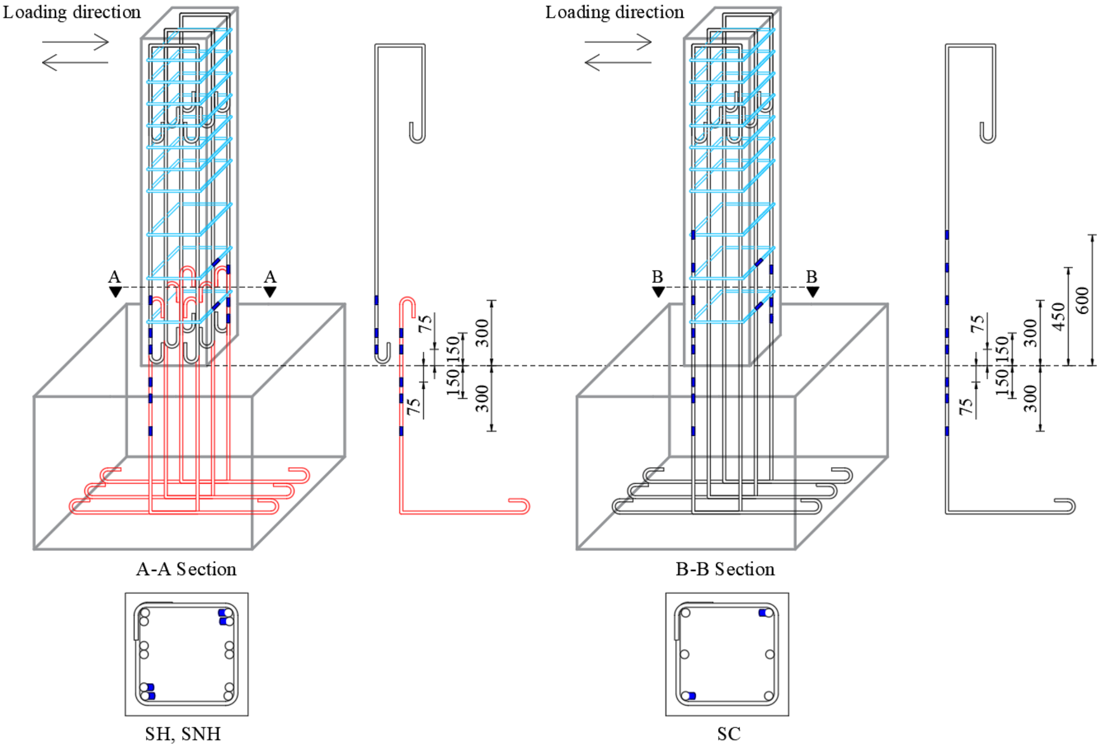


Figure 3 - Strain gauge positions (all dimensions in mm)

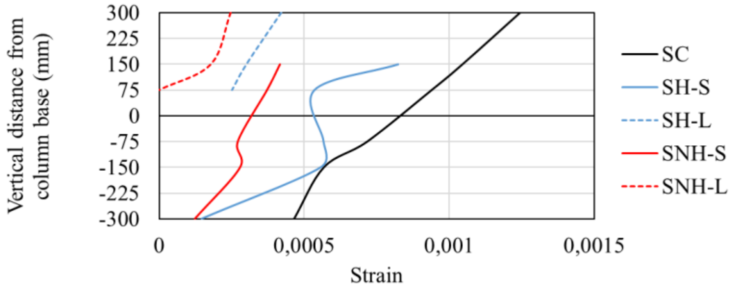


Figure 4 - Strain distribution along both starter and longitudinal bars at 1.0% drift ratio

3. TEST RESULTS

The test results are evaluated through the hysteretic lateral load–displacement curves, their envelopes, ultimate displacements and damage patterns. The lateral load-displacement relationships for all specimens are shown in Fig. 5. The lateral strengths for the columns SC, SH and SNH were recorded as around 44, 38 and 34.7 kN, respectively. The column with continuous bars (SC) exhibited around 20% higher lateral strength with respect to the lap-spliced columns. On the other hand, while the lap-spliced columns experienced a similar lateral strength, the presence of a hook resulted with a less steep descending branch in the hysteretic curves with respect to the no hook case. None of the columns exhibited a lateral strength degradation until a drift ratio of at least 0.75%. Afterwards, lap-spliced specimen with 180-degree hook (SH) and lap-spliced specimen with no hook (SNH) exhibited strength degradation due to weak bond stresses between concrete and plain reinforcing steel bars. Some typical damages were recorded and marked on the hysteresis loops for all specimens. In specimen with continuous longitudinal bars (SC), after 0.75% drift ratio, lateral strength was maintained longer with respect to the SH and SNH columns, until the buckling of the longitudinal reinforcement. In the lap-spliced specimen with 180-degree hook (SH), the first flexural crack appeared at a drift ratio of 0.25% (second pulling cycle). Then, a new crack occurred at the upper end of lap-splices around a drift ratio of 0.75% (first pulling cycle). Concrete cover spalled at a drift ratio of 1.5% (first pushing cycle). Eventually, column lost its lateral load capacity by development of concrete crushing and buckling of the longitudinal reinforcement at around 2% drift ratio (first pushing cycle). In the lap-spliced specimen having no hook (SNH), the first flexural crack appeared at a drift ratio of 0.25% (first pushing cycle). Then, a new crack occurred at the upper end of lap-splices around a drift ratio of 0.75% (first pushing cycle). Concrete cover spalled at a drift ratio of 1% (first pulling cycle). Eventually, column lost its lateral load capacity by the concrete crushing and buckling of the longitudinal reinforcement at around 1.5% drift ratio (second pulling cycle). In the specimen with continuous longitudinal bars (SC), the first flexural crack appeared at a drift ratio of 0.5% (first pushing cycle). Then, crushing of concrete occurred about a drift ratio of 1% (second pushing cycle). Concrete cover spalled at a drift ratio of 1.5% (second pulling cycle). Finally, column lost its lateral load capacity by the concrete crushing and buckling of the longitudinal reinforcement at around 3% drift ratio (first pushing cycle).

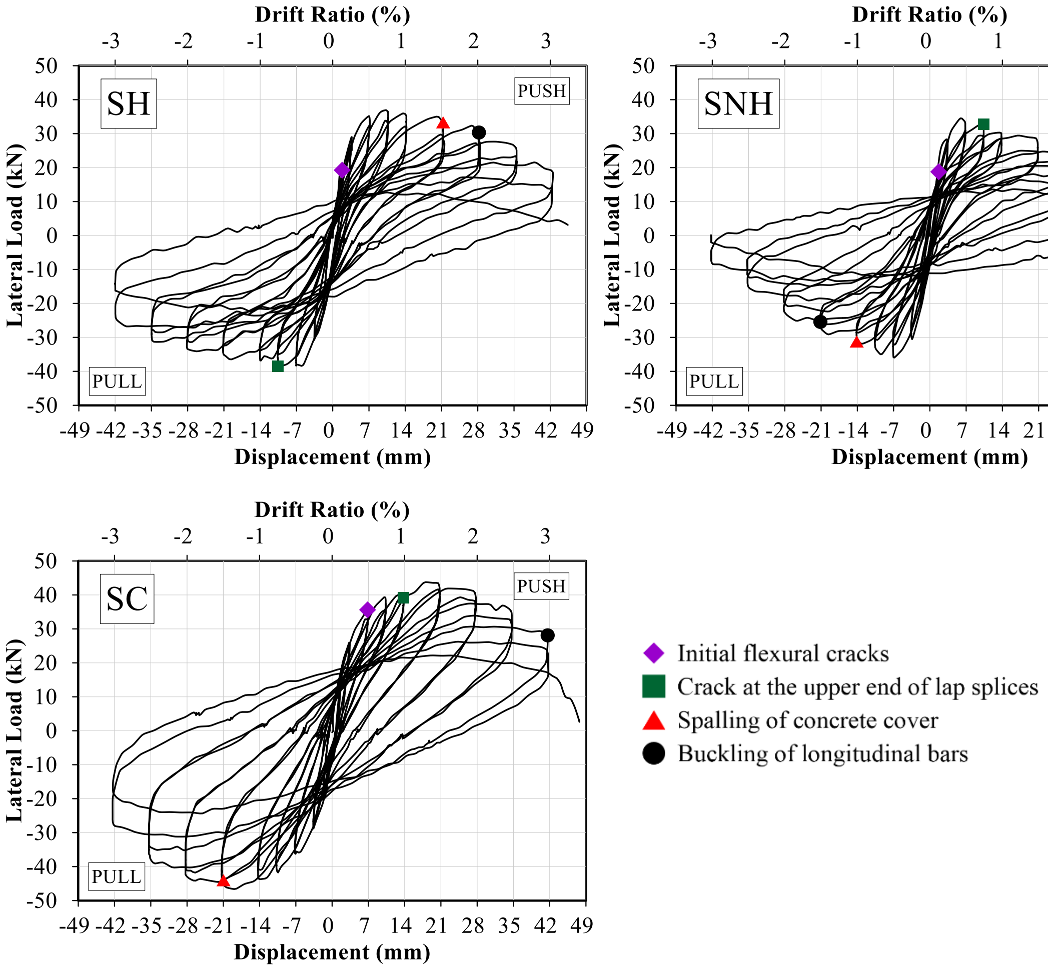


Figure 5 - Hysteretic lateral load-displacement response of the columns

The test results also demonstrated that the lateral displacements at failure (i.e., ultimate displacements defined as the displacements corresponding to the 20% lateral strength drop in the hysteretic response) is postponed in case using continuous lap-splice. The ultimate displacements for the columns SC, SH and SNH were recorded as around 36, 31 and 21 mm, respectively. Envelopes of the hysteretic curves are shown in Fig. 6. These curves demonstrate that columns with lap-splices did not reach their flexural strength and experienced earlier and more remarkable strength degradation with respect to the column reinforced with continuous longitudinal bars. On the other hand, presence of a 180-degree hook at the ends of spliced bars slightly reduced the negative influence of inadequate lap-splice length in terms of strength.

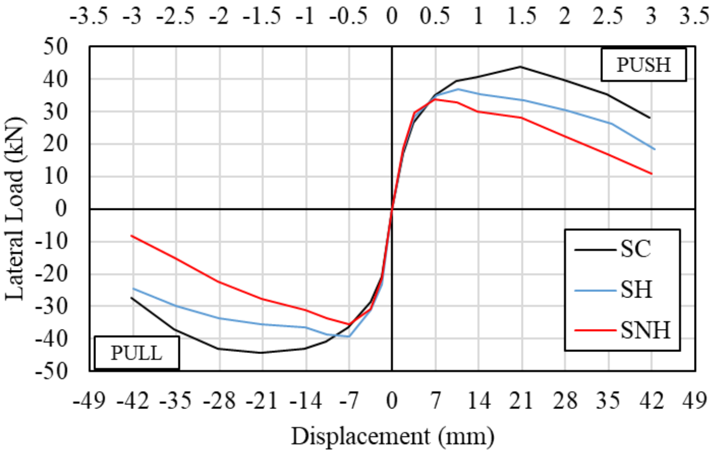


Figure 6 - Envelopes of the hysteretic curves

Observed damages on the column specimens at point of zero lateral displacement after 3% drift ratio in the negative loading direction are shown in Fig. 7. First flexural cracks on all specimens were formed at the level of transverse reinforcement. In larger drift ratios (around 2.5%), damages on the specimens were localized mainly at the tip of the starter bars and column-foundation interface due to the slippage of plain reinforcing bars at both along the foundation and the column height as shown in Fig. 4. Also, concrete covers of the specimens were spalled at around tip of the starter bars. None of the specimens experienced shear failure or noticeable shear damage.

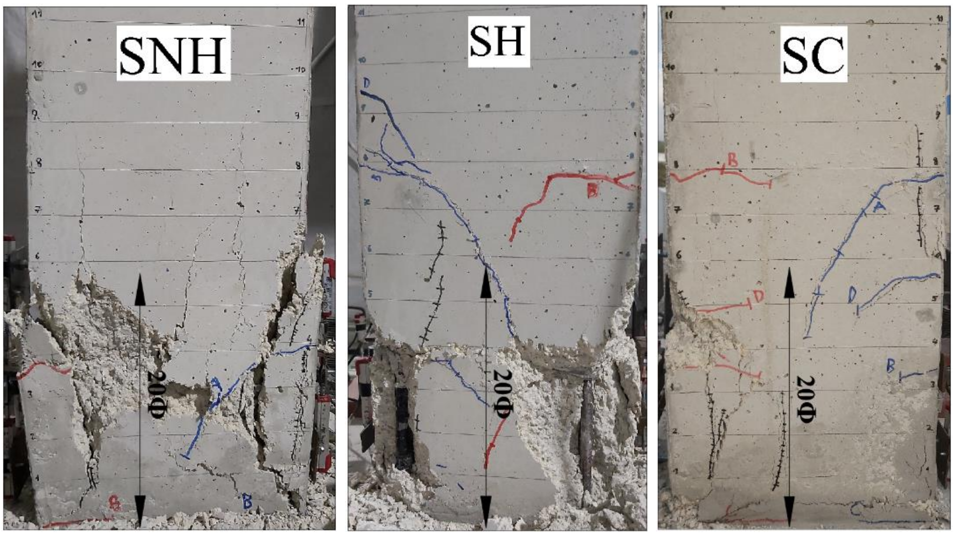


Figure 7 - Damage observed on the column specimens (at point of zero lateral displacement after 3% drift ratio)

4. CONCLUSIONS

This study aims to investigate the effects of two different lap-splice configurations on the seismic performance of substandard RC columns. Towards this aim, three full-scale columns were constructed to represent the typical characteristics of substandard RC columns were tested under constant axial loading and reversed cyclic displacement reversals simultaneously representing gravity loads and seismic actions, respectively. The following conclusions can be drawn from the findings of the study:

1. Columns with lap-splices, irrespective of being hooked or unhooked, did not reach their flexural strength and experienced earlier and more remarkable strength degradation with respect to the column reinforced with continuous longitudinal bars. The column with continuous bars (SC) exhibited around 20% higher lateral strength with respect to the lap-spliced columns. On the other hand, while the lap-spliced columns experienced a similar lateral strength, the presence of a hook resulted with a less steep descending branch in the hysteretic curves with respect to the no hook case.

2. Test results demonstrated that the flexural strength and deformation capacity of columns with lap-splices are affected by the presence of a 180-degree hook at the ends of the spliced bars. Presence of a 180-degree hook at the ends of spliced bars reduced the negative influence of inadequate lap-splice length in terms of strength.

3. The ultimate displacement for the columns is postponed in case using continuous lap-splice. The ultimate displacements for the columns SC, SH and SNH were recorded as around 36, 31 and 21 mm, respectively.

There is a need for further studies to better understand the influence of axial load ratio on the seismic behavior of the lap-spliced substandard columns.

5. ACKNOWLEDGMENTS

This study is supported by The Scientific and Technological Research Council of Turkey (TUBITAK) under the Grant No. 119M623. The contributions of Muhsin Can Luleci, Bilal Sari and Erkan Tore are gratefully acknowledged. The authors are also thankful to the support of Fibrobeton Yapi Elemanlari Co and Mr. Muhammed Marasli.

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