TENSION LAP SPLICES UNDER SEVERE LOAD REVERSALS

by

J.D. Aristizabal-Ochoa[I], A.E. Fiorato[II],
and W.G. Corley[III]

SUMMARY

This paper describes a test program to develop seismic design criteria for lap splices of reinforcing bars. Specifically, performance of tension lap splices under severe load reversals is being investigated. Behavior of eight specimens is described. Variables include load history, amount and configuration of lapped reinforcement, and amount of transverse hoop reinforcement around the lapped bars.

Tests were performed on reinforced concrete column elements under reversing axial loads. Columns had cross-sectional dimensions of 12x12 in. (305 x 305 mm). Longitudinal reinforcement consisted of either four No. 8 bars or eight No. 6 bars.

Results indicate that distribution of transverse hoop reinforcement significantly influences performance. Offset reinforcing bars also have a significant effect. Specimens with Class C lap splices and special transverse hoop reinforcement performed well under monotonic and reversing loads.

INTRODUCTION

As part of an investigation of reinforced concrete structural walls used as lateral bracing in earthquake-resistant buildings, lap splices of reinforcing bars were evaluated. The specific problem considered is the use of tension lap splices in regions where main reinforcement yields under severe stress reversals. This can occur, for example, at the base of structural walls where splices of vertical reinforcing bars are often unavoidable. During severe earthquakes, overturning forces can induce inelastic stress reversals in these bars. The designer has no guidance on effectiveness of splices in this critical region.

OBJECTIVES AND SCOPE

Objectives of this investigation were:

1. To determine effects of reversing loads on behavior of tension lap splices.
2. To develop design criteria for tension lap splices in earthquake resistant structures.

To achieve these objectives, a series of reversing load tests on specimens containing lap splices were performed. Variables included:

1. Load History. Histories corresponding to monotonic and severe reversing loads were applied.

[I] Former Structural Engineer, Structural Development Department.

[II] Manager, Construction Methods Section.

[III] Divisional Director, Engineering Development Division, Construction Technology Laboratories, A Division of the Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077, USA

2. Longitudinal Reinforcement. Configurations using either four No. 8 bars or eight No. 6 bars were tested.
3. Transverse Reinforcement. Amount of transverse reinforcement ranged from that required for ordinary column ties to that required for confinement hoops.

OUTLINE OF TEST PROGRAM

Eight specimens listed in Table 1 were tested. Four were subjected to monotonic loading and four were subjected to severe load reversals.

Test Specimens

Tests were made on I-shaped specimens as shown in Figs. 1 and 2. The splice test region was at midlength of the column portion of the specimen. Specimens were instrumented to measure applied loads, axial elongations, and steel strains.

As shown in Fig. 2, cross-sectional dimensions at the splice location were 12x12 in. (305 x 305 mm). Length of the test section was 96 in. (2.44 m). Amount of longitudinal reinforcement within the splice length was 4.4% for specimens with No. 8 bars and 4.9% for specimens with No. 6 bars. Reinforcement conformed to ASTM Designation: A615, Grade 60. Concrete for all specimens had a design strength of 3000 psi. Measured material properties are given in Tables 2 and 3.

Specimen Design

Splices were designed as Class C tension laps according to the 1977 ACI Building Code (1). This resulted in a 33-in. (0.84 m) lap for specimens with No. 6 bars and a 60-in. (1.52 m) lap for specimens with No. 8 bars.

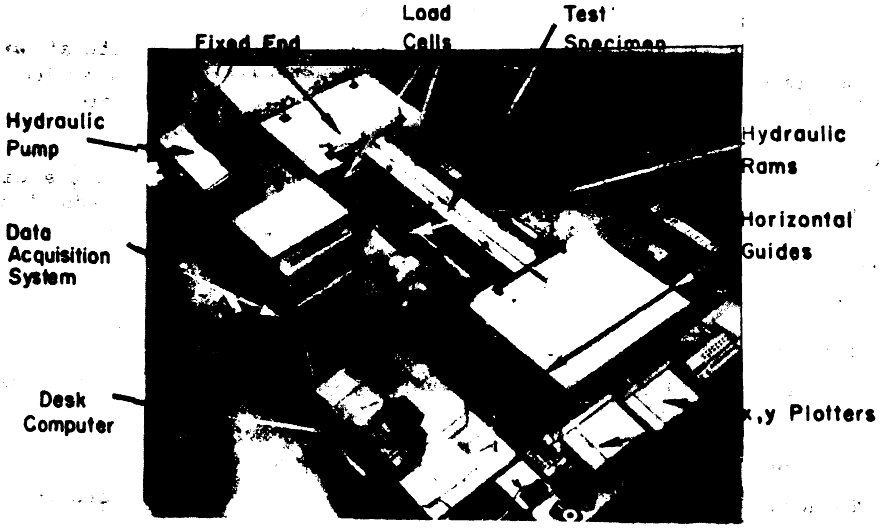


Fig. 1 Test Setup

TABLE 1 - TEST SPECIMENS

Specimen[(a)]	Load History	Transverse Reinf.	Longitudinal[(b)] Reinf.
S6-1	Monotonic	No. 3 @ 2"	8 No. 6
S6-2	Reversing	No. 3 @ 2"	8 No. 6
S6-3	Reversing	No. 3 @ 4"	8 No. 6
S6-4	Monotonic	No. 3 @ 4"	8 No. 6
S8-1	Monotonic	No. 3 @ 2"	4 No. 8
S8-2	Reversing	No. 3 @ 2"	4 No. 8
S8-3	Monotonic	No. 3 @ 12"	4 No. 8
S8-4	Reversing	No. 3 @ 4"	4 No. 8

(a) All specimens 3000 psi (20.7 MPa) design compressive strength concrete.
(b) All bars spliced at same location (100% spliced).
(c) 1 in. = 25.4 mm

TABLE 2 - CONCRETE PROPERTIES

Specimen	Age At Test (days)	Compressive Strength, f'_c (psi)	Modulus of Rupture, f_r (psi)	Split Cylinder Test, f_s (psi)
S6-1	24	3300	510	430
S6-2	28	3980	460	340
S6-3	43	3520	410	490
S6-4	41	3280	370	420
S8-1	50	3340	460	430
S8-2	34	4480	420	560
S8-3	35	4520	400	540
S8-4	24	3530	490	450

(a) Average properties for center part of the specimen.
(b) 1000 psi = 6.895 MPa.

TABLE 3 - REINFORCING BAR PROPERTIES

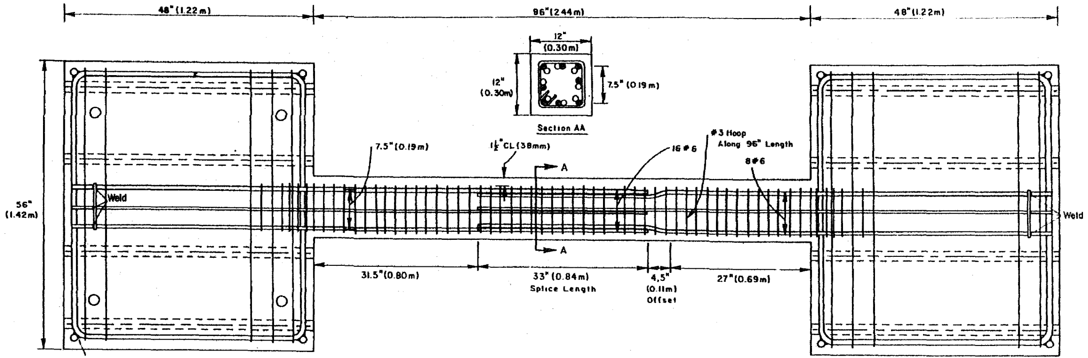
Bar Size	f_y (ksi)	f_{su} (ksi)	E_s (ksi)	Elongation (%)
No. 3	73.7	109.8	29,800	13
No. 6	69.9	107.4	29,600	13
No. 8	68.2	111.4	30,100	13

(a) 1.0 ksi = 6.895 MPa

TABLE 4 - SUMMARY OF TEST RESULTS

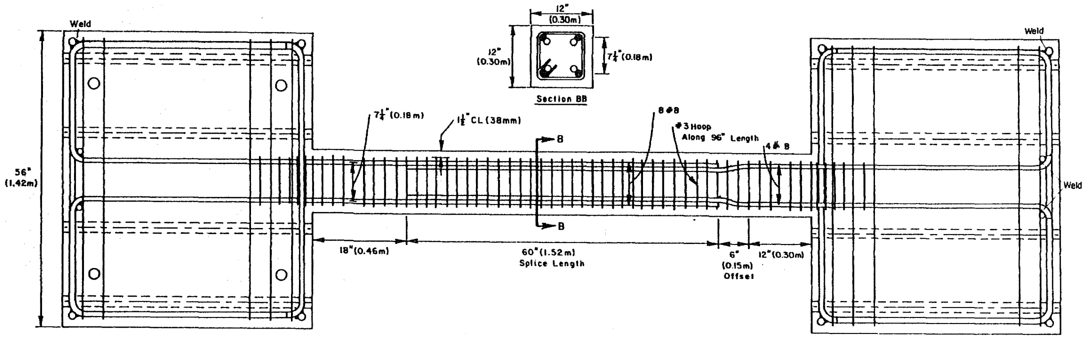
Specimen	Cracking Load (kips)		Full Yield Load (kips)		Maximum Load (kips)		Observed Mode of Failure[(c)]
	Observed	Calculated[(a)]	Observed	Calculated[(b)]	Observed	Calculated[(b)]	
S6-1	47	61	246	246	357	378	Splice [M]
S6-2	47	49	246	246	357	378	Bar Fracture [6]
S6-3	46	71	246	246	302	378	Splice [6]
S6-4	46	60	246	246	298	378	Splice [5]
S8-1	44	62	216	216	330	352	Bar Fracture [M]
S8-2[(d)]	46	80	216	216	325	352	-- [6]
S8-3	46	78	211	216	280	352	Splice [M]
S8-4[(e)]	46	65	212	216	261	352	Bar Fracture [3]

(a) Based on split cylinder tensile strength.
(b) Based on average properties of reinforcing steel.
(c) Number within brackets indicates number of fully reversed cycles applied to specimen prior to destruction. M = monotonic load.
(d) Loading apparatus became unstable after initial six cycles applied.
(e) A corner bar fractured at the offset during the first half of the fourth cycle.
(f) 1 kip = 1000 lb = 4.448 kN



(a) S6 Specimen

See Table 2 for hoop spacing



(b) S8 Specimen

Fig. 2 Reinforcement Details of Test Specimens

Transverse reinforcement in Specimens S6-1, S6-2, S8-1, and S8-2 consisted of hoops spaced 2 in. (51 mm) on centers. Rectangular hoops were made from No. 3 bars. Volumetric hoop reinforcement ratios in these specimens met requirements of the 1976 Uniform Building Code (2). Hoops provided 70% of reinforcement required by the 1977 ACI Building Code (1).

To investigate effects of transverse reinforcement, four specimens were built with fewer hoops. In Specimens S6-3, S6-4, and S8-4, No. 3 hoops were spaced at 4 in. (102 mm) on centers. In specimen S8-3, No. 3 hoops were spaced at 12 in. (305 mm) on centers, which is the maximum spacing permitted for column ties (1).

As is common practice, corner longitudinal bars had offsets at the start of the lap. This is shown in Fig. 2. Slope of the inclined portion of the bars with the longitudinal axis of the column was 1:6. Interior bars were not offset.

Loading

Two load histories were used. In tensile monotonic loading tests, specimens were initially loaded in increasing force increments. Subsequent to yielding, loading was controlled by increments of axial elongation. Elongation was increased in equal increments until the specimen was destroyed. In reversing loading tests, specimens were subjected to six fully reversed cycles. In tension, three cycles at yield were alternated with three cycles at 1.25 times yield. In compression, six cycles at a peak load of approximately 200 kips (890 kN) were applied. After six cycles, specimens were subjected to slowly increased tensile force until they were destroyed.

OBSERVED BEHAVIOR

Capacity of each specimen was limited either by bar fracture or pullout of spliced bars. Bar fracture occurred at the offset. Pullout of spliced bars was associated with longitudinal splitting of the concrete. A general discussion of effects of significant variables is presented in the following sections. Test results are summarized in Table 4.

Effects of Load History

One of the main objectives of this experimental investigation was to determine effects of severe load reversals on performance of tension lap splices. Performance of specimens subjected to reversing loads was similar to that for specimens subjected to monotonic tensile loading.

Figure 3 shows load versus total elongation of nominally identical specimens subjected to different loading histories. Hysteresis loops, shown by solid lines, correspond to specimens subjected to reversing loads. Broken lines correspond to companion monotonic load tests. Results in Fig. 3 and Table 4 show that strength was not affected by load history. However, final elongation of specimens subjected to monotonic loading was slightly larger than for companion specimens subjected to load reversals.

Effects of Longitudinal Reinforcement

Amount and distribution of lapped reinforcement were important factors.

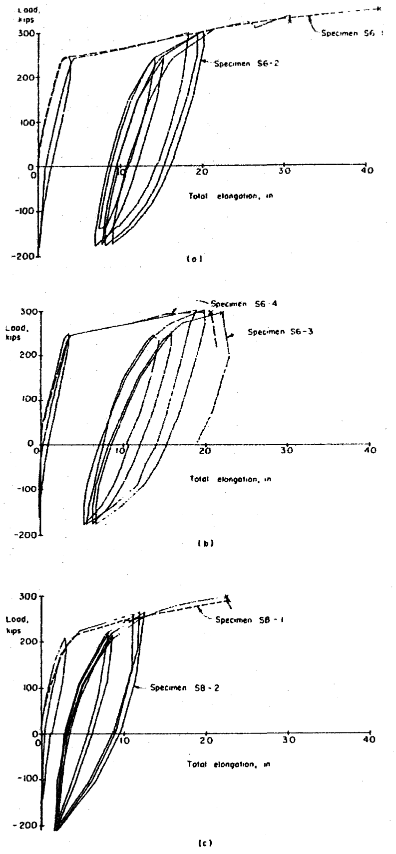


Fig. 3 Effects of Load Reversals

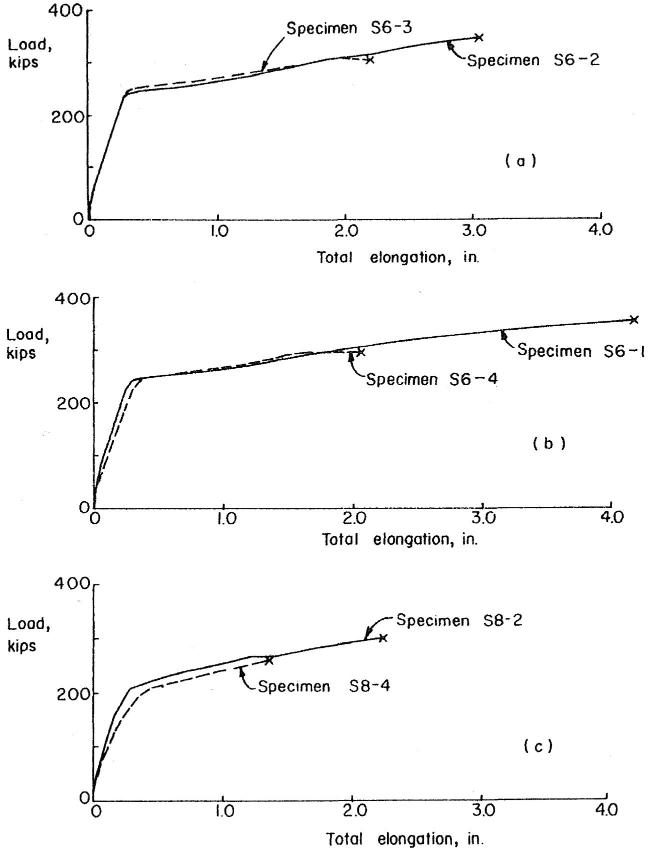


Fig. 4 Effects of Transverse Reinforcement

As expected, the larger the lapped bars relative to the size of the cross-section, the larger the bursting forces in the concrete, particularly at the offset end.

Main differences between S8 Specimens and S6 Specimens were bar size, presence of interior bars in S6 Specimens, and relative size of the offset with respect to the cross-section. Figure 2 shows reinforcement in S8 and S6 Specimens.

In two S8 Specimens bar fracture occurred at the offset. In Specimen S8-3, which had very light transverse reinforcement, longitudinal reinforcement slipped. Extent of bursting at the offset was more severe in S8 Specimens than in S6 Specimens.

Except for S6-2, capacity of S6 Specimens was limited by slip of interior bars. Splitting cracks appeared along interior bars near the offset as first yield of longitudinal reinforcement occurred. At very high inelastic tensile loads, longitudinal splitting propagated from both end regions into the splice length. As loads approached ultimate, interior spliced bars slipped, and load was transferred to corner bars causing them to fracture. Longitudinal splitting was not as well contained for interior bars as it was for corner bars. This is attributed to the fact that corner bars were confined in two directions by transverse hoops.

Effects of Transverse Reinforcement

Amount and distribution of transverse reinforcement are critical to deformation capacity, strength and behavior. Transverse reinforcement controls longitudinal splitting, bar slip, and yield penetration along the splice. In particular, longitudinal lapped bars located within corners of hoops have less tendency to slip. Intensity of strains at end regions of the splice indicated that location of transverse reinforcement is a critical factor. From measurements of strains in transverse reinforcement, it was apparent that hoops at the ends of the splice were more effective than interior hoops.

For the amounts of transverse reinforcement used in the tests, reduction in the number of uniformly distributed hoops caused a relatively small reduction in load carrying capacity of the tension lap splice. Comparison of Specimens S6-2 and S6-3 in Table 4 shows that a 50% reduction in transverse reinforcement caused a reduction of only 15% in strength of the splice. Similar effects were observed in monotonically loaded Specimens S6-1 and S6-4.

Comparison of Specimens S8-1 and S8-3 shows that an 83% reduction in transverse reinforcement caused a reduction of only 15% in strength for monotonically loaded Class C tension laps. Similar comparisons for Specimens S8-2 and S8-4 indicate a 20% reduction for a 50% reduction in hoops.

Transverse reinforcement had a significant effect on deformation capacity of the specimens. Figure 4a shows applied axial load versus total elongation envelopes for Specimens S6-2 and S6-3. As expected, Specimen S6-2, containing more hoops, attained a higher ductility than Specimen S6-3. A similar trend was observed for Specimens S6-1 and S6-4, as shown in Fig. 4b, and Specimens S8-2, and S8-4, as shown in Fig. 4c.

CONCLUSIONS

The following observations are based on results of eight tests:

1. Specimens designed as Class C lap splices with transverse reinforcement meeting seismic design requirements of the 1976 Uniform Building Code(2) performed well under monotonic and reversing loads. Strength of these specimens varied from 92% to 94% of the average tensile strength of the longitudinal reinforcement. Measured ultimate loads ranged from 169% to 174% of the design yield.
2. Strength of specimens was not affected significantly by load history.
3. All specimens experienced large post-yield elongations. Specimens subjected to monotonic loading exhibited slightly larger axial deformation capacity than those subjected to load reversals.
4. Use of offset bars at the end of the lap caused severe local distress. The extent of damage was larger in specimens with large bars. Moreover, this detail may lead to low cycle fatigue under load reversals.
5. In an eight bar arrangement with 100% of the bars spliced, slip of interior bars controlled capacity. Splitting cracks first appeared along interior bars at the offset and then propagated from both end regions into the splice. Cracks were first observed as the load approached yield. As the tensile load approached ultimate, interior spliced bars slipped and transferred load to corner bars. Longitudinal splitting was not as well contained for interior bars as it was for corner bars.
6. Transverse reinforcement was effective in controlling longitudinal splitting and bar slip as well as yield penetration along the spliced bars.
7. Amount and distribution of transverse reinforcement have a critical affect on behavior of lap splices. An insufficient amount of hoop reinforcement at ends of a splice can lead to reduction in deformation capacity and strength, and to severe damage within the splice region. From measurements of strains in transverse reinforcement, it is evident that hoops at the ends of a splice are more effective than interior hoops in resisting splitting and bursting of concrete.
8. Transverse hoops must be in contact with longitudinal bars to be effective.

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