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EARTHQUAKE RESISTANT STRUCTURAL WALLS- TESTS OF LAP SPLICES

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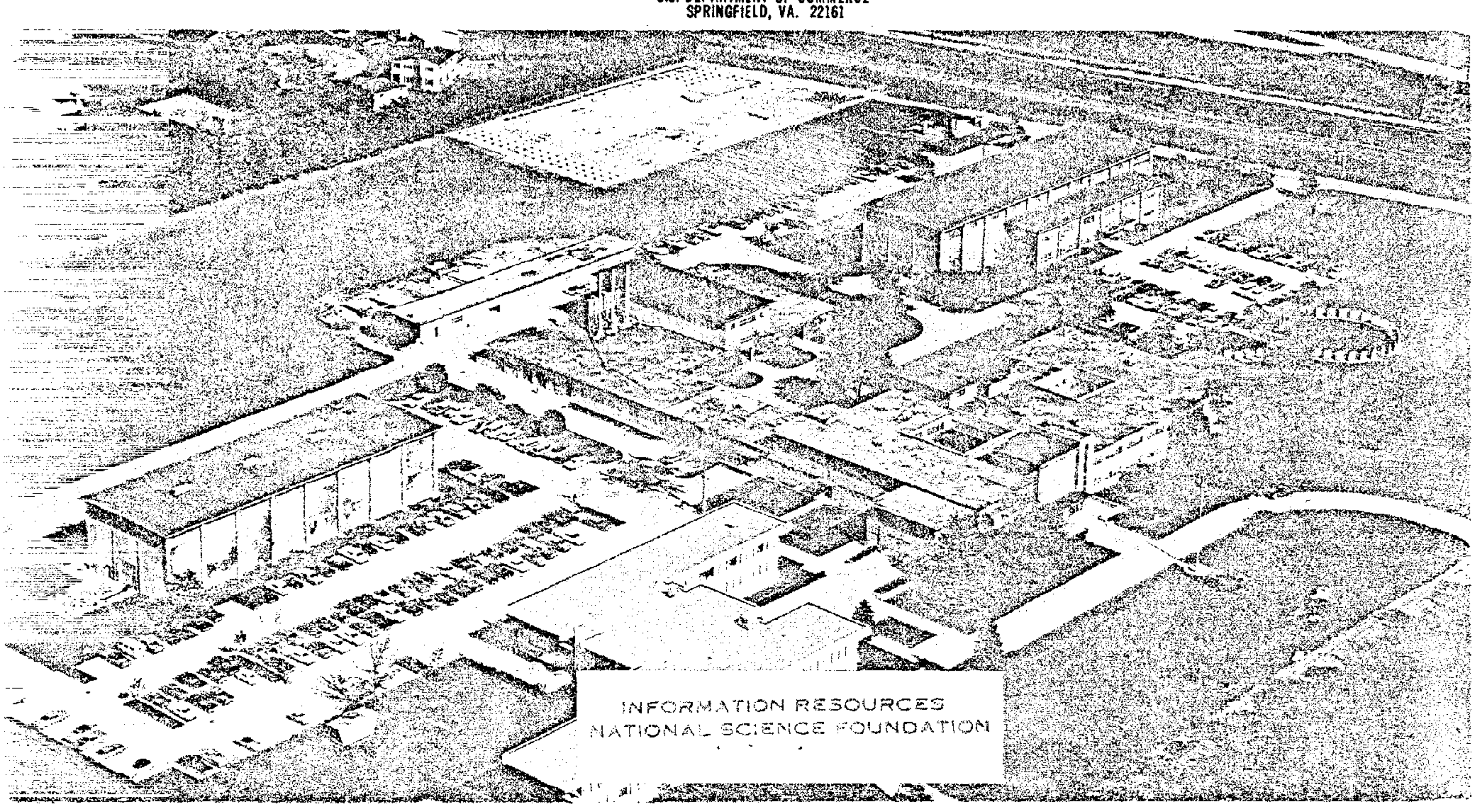

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16. Abstract (Limit: 200 words)

A test program to develop seismic design criteria for lap splices of reinforcing bars is described. Specifically, the effectiveness of tension lap splices under inelastic stress reversals is evaluated. Variables include load history, amount and configuration of lapped reinforcement, and amount of transverse hoop reinforcement around the lapped bars. Tests were performed on eight reinforced concrete column elements. Columns had cross-sectional dimensions of 12 x 12 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 axial loads.

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Concrete structures	Design criteria	Ductility
Reinforced concrete	Walls	Columns (supports)

b. Identifiers/Open-Ended Terms

Lap splices

Earthquake Hazards Mitigation

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EARTHQUAKE RESISTANT STRUCTURAL WALLS - TESTS OF LAP SPLICES

by

J. D. Aristizabal-Ochoa, A. E. Fiorato, and W. G. Corley*

HIGHLIGHTS

This report describes results of a test program to develop seismic design criteria for lap splices of reinforcing bars. The full-scale tests are part of an investigation of reinforced concrete structural walls used as lateral bracing in earthquake-resistant buildings.

The specific problem considered in this investigation is use of tension lap splices in regions of potentially severe stress reversals. This situation occurs, for example, at the base of tall structural walls where splices of vertical reinforcing bars are often used. Figure 1 illustrates this condition. During severe earthquakes, overturning forces can induce inelastic stress reversals in the vertical bars. At present, the designer has no guidance on effectiveness of splices in this critical region.

This report presents results of a test program to evaluate effectiveness of lap splices under inelastic stress reversals. It includes a description of eight 12-in. (305-mm) square column elements subjected to axial loads.

*Respectively, Former Structural Engineer, Structural Development Section; Manager, Construction Methods Section; and Divisional Director, Engineering Development Division, Portland Cement Association, Skokie, Illinois.

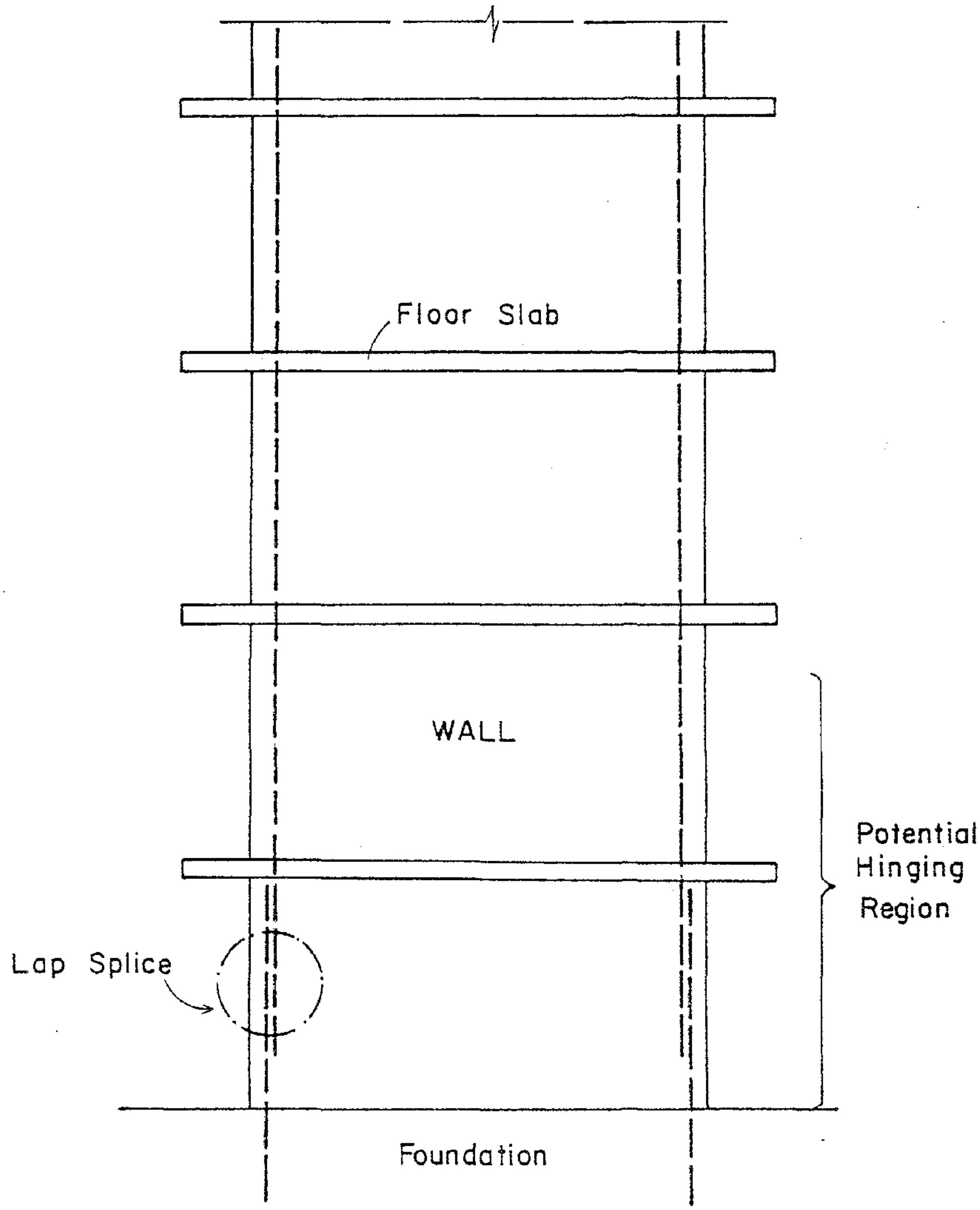

Fig. 1 Splice in Critical Region Near Base of Structural Wall

Variables were amount and configuration of lapped longitudinal reinforcement, amount of transverse hoop reinforcement around the longitudinal reinforcement, and load history.

Specimens had Class C tension lap splices in conformance with the 1977 ACI Building Code.(1)* Lapped longitudinal reinforcement included No. 8 and No. 6 bars. In each case 100% of the bars were spliced at the same location. Following common practice, corner bars were offset at the end of the lap. Offset length was six times the bar diameter. Amount of transverse reinforcement varied from that required for seismic design conditions to maximum spacing for column ties. Four tests under monotonic loading and four under severe reversing loading were made. Reinforcement with a nominal yield of 60 ksi (414 MPa) was used. Nominal concrete strength was 3,000 psi (20.7 MPa).

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* Numbers in parentheses correspond to references at the end of the report.

CURRENT BUILDING CODE PROVISIONS

The 1977 ACI Building Code[1] provisions for tension lap splices of flexural members are summarized in Table 1. These provisions are similar to those in the 1976 Uniform Building Code.[2] Three classes of lap splices are defined. No lap splices are permitted for bars larger than No. 11.

For sections where the area of tensile steel provided is equal to or greater than two times that required, two cases are considered. When 75% or less of the bars at the section in question are interrupted, a Class A splice is required. This splice has a lap length equal to the bar development length, ℓ_d. When more than 75% of the bars at a section are interrupted, a Class B splice is required. The lap length is then 1.3 ℓ_d.

For sections where the area of tensile steel provided is less than two times that required, two more cases are defined. When 50% or less of the bars are interrupted, a Class B splice is required. When more than 50% of the bars are spliced, a Class C splice must be used. This splice has a lap length of 1.7 ℓ_d.

Seismic design provisions in Appendix A of the 1977 ACI Building Code[1] also require that lap lengths be at least 24 nominal bar diameters or 12 in. (305 mm).

The basic intent of the building code provisions is to discourage use of tensile splices in regions of critical stress and to encourage staggering of splices.

TABLE 1 - TENSION LAP SPLICES ACCORDING TO 1977 ACI BUILDING CODE

$\frac{A_s \text{ provided}}{A_s \text{ required}}$	Maximum percent of A_s spliced within required lap length		
	50	75	100
Equal to or greater than 2	Class A	Class A	Class B
Less than 2	Class B	Class C	Class C

Where:

A_s provided/A_s required = ratio of area of reinforcement provided to area of reinforcement required by analysis of splice location.

Class A splice = 1.0 ℓ_d

Class B splice = 1.3 ℓ_d

Class C splice = 1.7 ℓ_d

ℓ_d = development length, in. = $\frac{0.04\ A_b f_y}{\sqrt{f'_c}}$

but not less than 0.0004 $d_b f_y$ for No. 11 bars or smaller in normal weight concrete.

f_y = specified yield strength of reinforcement, psi

d_b = nominal diameter of bar, in.

A_b = area of individual bar, sq. in.

f'_c = specified compressive strength of concrete, psi

For seismic conditions, applicability of current code provisions for tensile laps needs to be clarified. The following questions arise:

(1) Code lap lengths are based on development of 125% of the yield stress of the bar. Is this appropriate for seismic conditions where severe overloads can occur?

(2) Experimental investigations[3] indicate a significant improvement in performance with ordinary transverse reinforcement. For seismic design, unusually large amounts of transverse reinforcement are used. What is the effect of such reinforcement on performance of lap splices?

(3) What are effects of load reversals on the performance of lap splices?

LITERATURE REVIEW

A review of literature on lap splices of reinforcing bars indicates that very little work has been done to determine performance under seismic loading conditions. Appendix A is a list of references covering the topic of lap splices.

An evaluation of development length and lap splices has been reported by Orangun et al.[3] This paper describes derivation of an equation for development length that includes effects of concrete cover, bar spacing, and amount of uniformly distributed transverse reinforcement. However, the recommendations are based on tests of monotonically loaded members. They must be reevaluated for members subjected to seismic loading.

Test of lap splices under monotonic compressive loads have been reported by Arthur and Cairns.[4] They concluded that:

(1) Forces in compression lap splices are transferred by bond stresses around the circumference of the bars and by end-bearing of the bars on the concrete.

(2) Transfer of forces causes bursting stresses on the surrounding concrete.

(3) Strength in bond and end-bearing is dependent on the resistance available to counteract bursting stresses.

(4) Transverse reinforcement located at ends of the splice is most effective in resisting bursting stresses.

Arthur and Cairns developed an expression to predict stresses in the main steel. This expression includes contributions of lateral reinforcement, bond, and end bearing. They also recommended that one third of required transverse reinforcement be placed within a distance of 15% of the lap length from each end of the splice.

Tests of tension lap splices in beams have recently been reported by Betzle.(5) His tests included beams longitudinally reinforced with No. 5 and No. 9 bars without transverse reinforcement. Specimens were subjected to monotonic loading. Betzle concluded that bond stresses in the concrete and force transfer between lapped bars are mainly concentrated at the ends of the splice.

Tests of bond and anchorage of reinforcing bars under inelastic reversals of load have been reported by Ismail and Jirsa,(6) Hassan and Hawkins,(7) and Popov.(8) These tests indicate that rate of bond deterioration and response of anchored bars are significantly affected by loading history. Slip and deformation of anchored bars under load reversals were observed to have substantial influence on hysteretic response of the members tested. This was also observed in cantilever beam tests by Brown and Jirsa.(9) They concluded "Deformation of the steel in the anchorage zone (within the fixed end) contributed significantly to the total deformation and to the energy absorbing capacity of the specimens."

The conclusion is that, for seismic conditions, the load versus slip relationship of bars is of prime importance. Brown and Jirsa,(9) and Hawkins(10) also conclude that for cyclic inelastic loads it may be necessary to increase embedment lengths required by the 1977 ACI Building Code.(1)

Tests to determine effects of inelastic stress reversals on bond and anchorage are relevant to the problem of using lap splices under seismic conditions. However, a comprehensive evaluation of performance of lap splices under load reversals requires data from tests of spliced members under loading conditions simulating those that could occur during an earthquake. It is for this purpose that the current program was undertaken.

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 - Tests using load histories corresponding to monotonic and severe reversing loads were made.

(2) Longitudinal Reinforcement - Variations in longitudinal reinforcement included bar size and number of bars in the cross section.

(3) Transverse Reinforcement - The amount and configuration of transverse reinforcement ranged from that required for ordinary column ties to that required for special seismic confinement hoops.

Table 2 lists the variables considered in this experimental program.

TABLE 2 - TEST SPECIMENS

Specimen[1]	Load History	Transverse Reinf.	Longitudinal[2] 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

Notes: (1) All specimens 3,000 psi (20.7 MPa) design compressive strength concrete.

(2) All bars spliced at the same location. 100% Bar Splicing.

(3) 1 in. = 25.4 mm

OUTLINE OF TEST PROGRAM

A total of eight specimens were tested. 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 with a nominal yield of 60 ksi (414 MPa) was used. Nominal concrete strength was 3,000 psi (20.7 MPa). Four specimens were subjected to monotonic loading and four were subjected to severe loading reversals. Test specimens, test setup, and test procedure are described below.

Test Specimen

Tests were performed on I-shaped specimens as shown in Figs. 2, 3, and 4. Axial loads were applied through the two end blocks using two hydraulic rams. The splice test region was at the center of the column portion of the specimen.

The column portion had cross-sectional dimensions of 12x12 in. (305x305 mm) and a length of 96 in. (2.44 m). End blocks had dimensions of 48x56x12 in. (1.22x1.42x0.31 m).

Specimen Design

Cross sections at the location of the splices for the two types of specimens selected for testing are shown in Fig. 4. Specimens designated S6 consisted of eight No. 6 bars all spliced at the same location. Specimens designated S8 consisted of four No. 8 bars all spliced at the same location. The number and size of the reinforcing bars were selected within capacity

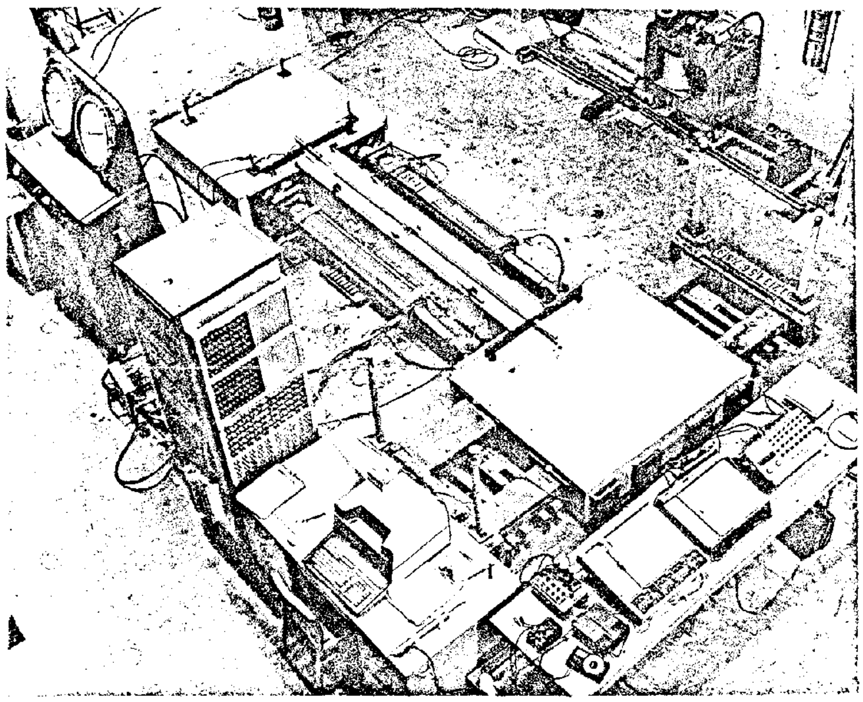

Fig. 2 Test Setup

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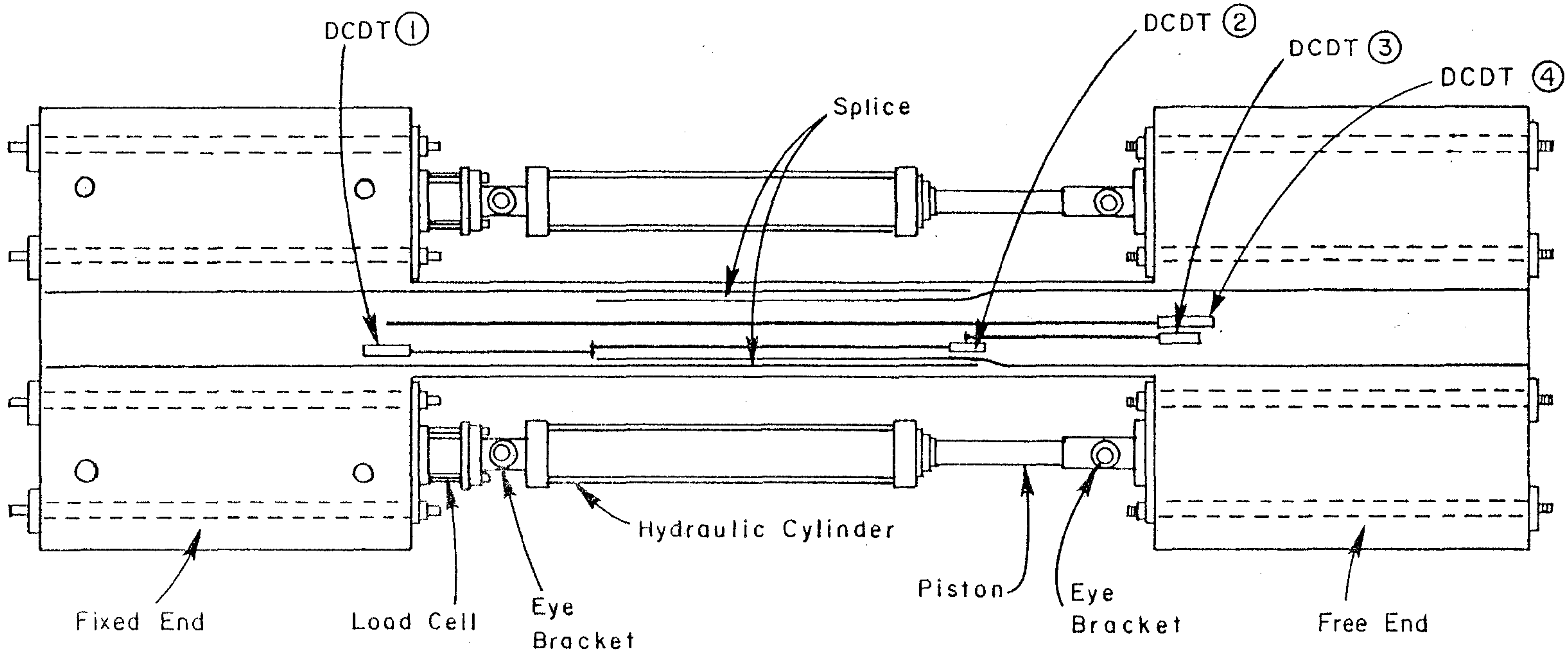
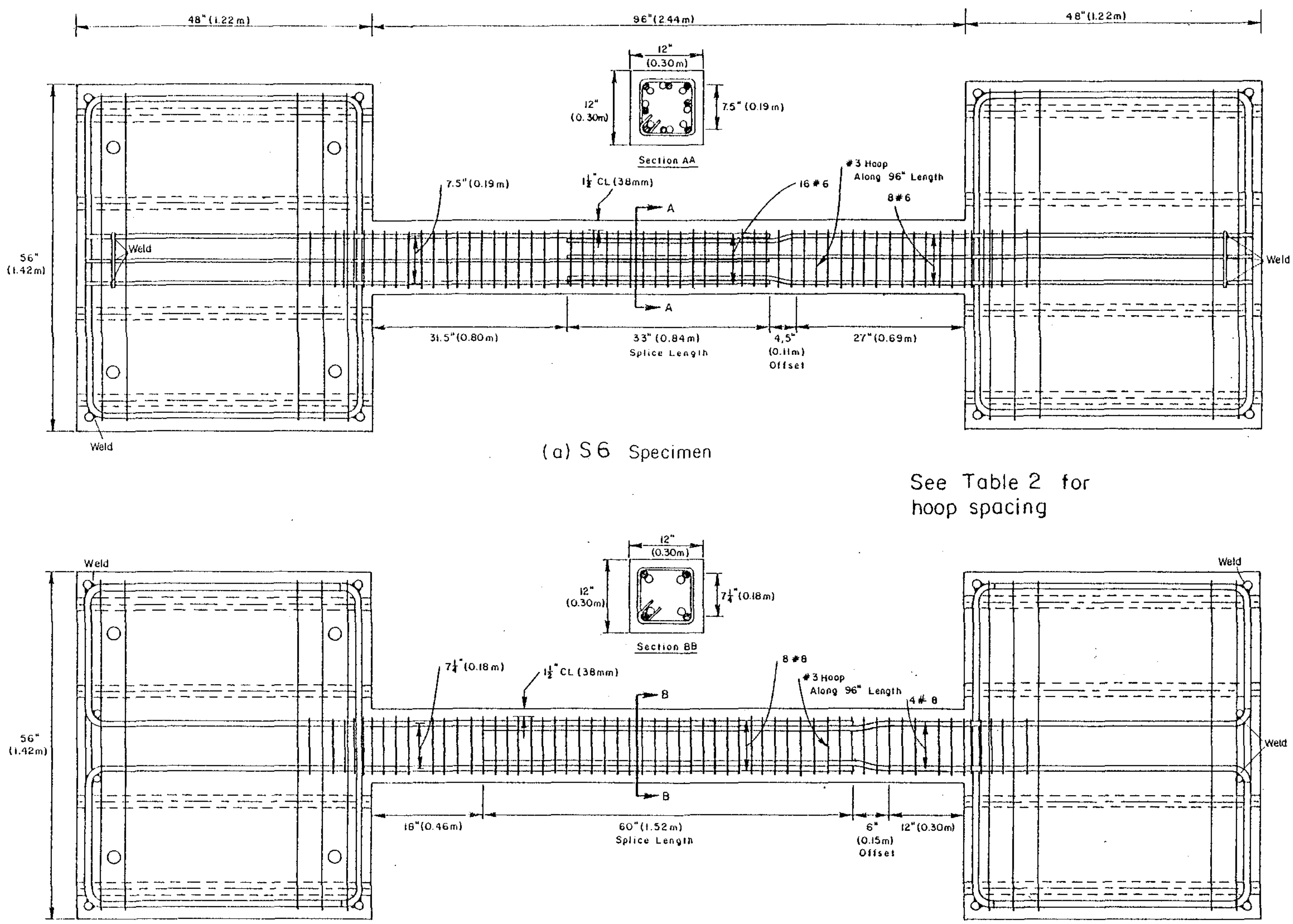


Fig. 3 Test Setup



(a) S6 Specimen

See Table 2 for
hoop spacing

(b) S8 Specimen

Fig. 4 Reinforcement Details of Test Specimens limits of existing laboratory equipment. The four bar and eight bar arrangements provide flexibility for considering different splice configurations.

Lap lengths corresponded to Class C tension lap splices according to the 1977 ACI Building Code.[1] This resulted in a 33-in. (0.84 m) lap for S6 specimens and a 60-in. (1.52 m) lap for S8 specimens.

Transverse reinforcement in Specimens S6-1, S6-2, S8-1, and S8-2 consisted of confinement hoops spaced 2 in. (51 mm) on centers. Rectangular hoops were made of No. 3 reinforcing bars. The volumetric hoop reinforcement ratio in these specimens met requirements of the 1976 Uniform Building Code.[2] It was 70% of that required by the 1977 ACI Building Code.[1]

To investigate effects of amount of transverse reinforcement on strength and behavior, Specimens S6-3, S6-4, S8-3, and S8-4 were built with less confinement. In Specimens S6-3, S6-4 and S8-4, transverse reinforcement consisted of No. 3 hoops spaced 4 in. (102 mm) on centers. In Specimen S8-3, it consisted of No. 3 hoops spaced 12 in. (305 mm) on centers. Confinement spacing in Specimen S8-3 corresponded to the maximum permitted for column ties in the 1976 Uniform Building Code and the 1977 ACI Building Code.

Corner longitudinal bars had offsets at the start of the lap as shown in Fig. 4. Slope of the inclined portion of the bars with the longitudinal axis of the specimen was 1:6, the maximum permitted by the 1977 ACI Building Code. Interior bars were not offset. Photographs of reinforcing cages at the location of the offsets are shown in Fig. 5. It was anticipated that local stress conditions at the offset would be critical to performance of the specimens.

The two end blocks were designed to avoid premature termination of tests because of failure of loading or supporting elements. Main longitudinal reinforcement in the specimens was anchored in the end blocks as indicated in Fig. 4.

Materials

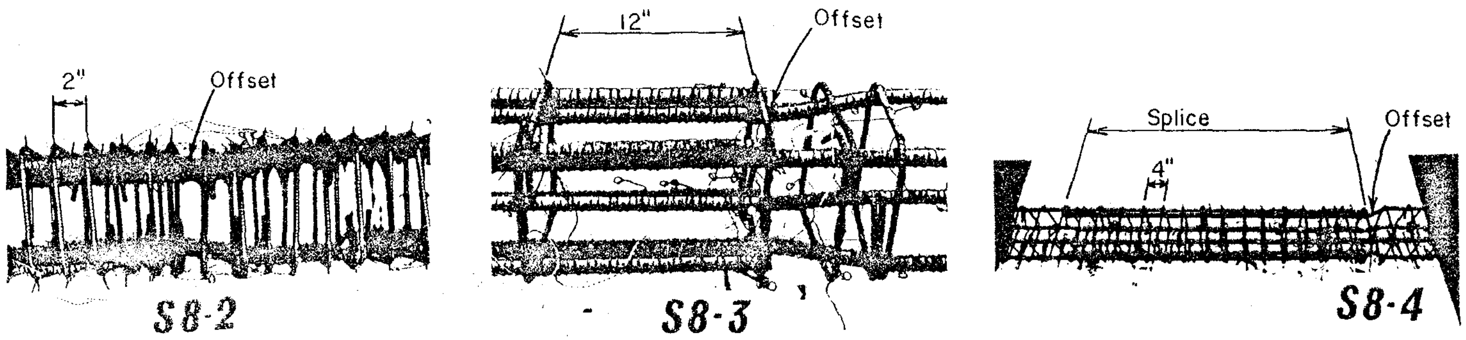
Concrete contained a blend of Type I portland cements, Elgin sand, and Elgin gravel aggregates.[11] Maximum aggregate size was 3/8 in. (10 mm). Compressive and splitting tensile strengths of the concrete were determined from tests on 6x12-in. (152x305 mm) cylinders. Modulus of rupture was determined from tests on 6x6x30-in. (152x152x762 mm) beams. Average properties of concrete used in each specimen are given in Table 3.

Bars conforming to ASTM Designation A615 Grade 60 were used as reinforcement. Measured physical properties of the reinforcement are summarized in Table 4.

Construction

Test specimens were constructed and cast in a horizontal position as shown in Fig. 6. Reinforcing cages for the center part of the specimen and for the two ends were fabricated as a unit and then placed in the form. Before casting, lifting eyes and inserts for attaching the loading system were placed in position.

(a) Offset in S6 Specimens



(b) Offset in S8 Specimens

Fig. 5 Offset of Longitudinal Reinforcement

TABLE 3 - CONCRETE PROPERTIES FOR TEST SPECIMENS

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

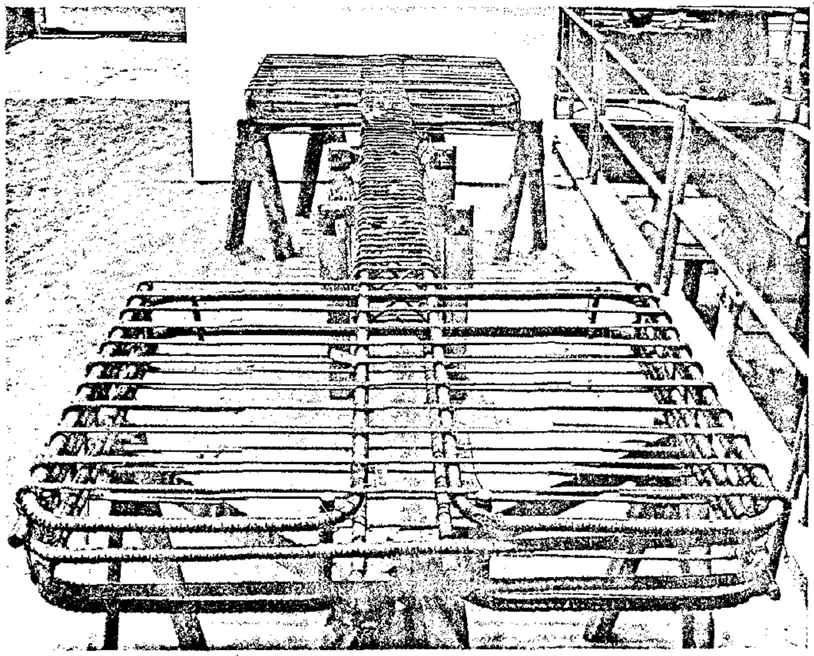
Notes: (1) Average properties for center part of the specimen.

(2) 1000 psi = 6.895 MPa.

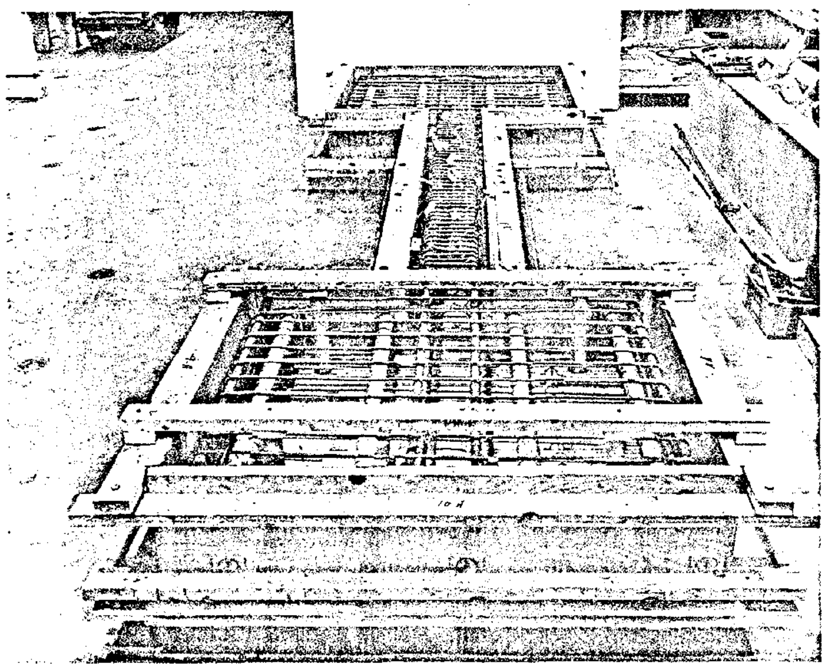
TABLE 4 - REINFORCING BAR PROPERTIES FOR TEST SPECIMENS

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

1.0 ksi = 6.895 MPa



(a) Reinforcing Cage



(b) Reinforcing Cage in Form

Fig. 6 Test Specimen S8-1 Prior to Casting

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Each specimen was cast using ten batches of concrete. Properties of the concrete were determined from batches used in the center part of the specimen. After casting, specimens were covered with polyethylene sheets and cured for one week. Specimens were then stripped and moved to the test location.

Test Setup

A photograph of a specimen ready for testing is shown in Fig. 2. Specimens were tested in a horizontal position. One end was fixed to the floor. The other was supported on thrust bearings and guided by rollers to prevent end rotation. Specimens were subjected to axial loading using two hydraulic rams controlled by a hydraulic pump.

Instrumentation

Specimens were instrumented to measure applied loads, axial elongations, and steel strains. Readings from each sensor were recorded by a VIDAR digital data acquisition system interfaced with an HP9830A calculator. Data were stored on tape cassettes for subsequent analysis.

Total and relative axial elongation of the column portion of the each specimen were measured using the system of external gages shown in Fig. 3. Elongations were measured with direct current differential transducers (DCDT).

Strain gages were placed on both longitudinal and transverse reinforcement.

Loading

Each test specimen was loaded axially with forces applied through the end blocks. Two loading histories were used. These are termed tensile monotonic (M), and severe reversing loading (SR).

In tensile monotonic loading tests, specimens were initially loaded in increasing force increments. Increments were determined by dividing the calculated yield load by 15. The first three or four increments were below the cracking load. Subsequent to yielding, loading was controlled by increments of axial elongation. Elongation, which was controlled by manually closing a valve in the hydraulic pressure line, was increased until the specimen was destroyed.

In the severe reversing loading tests, specimens were subjected to six reversing cycles. A representative SR loading history is shown in Fig. 7. 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 monotonic tensile loading until they were destroyed.

Specimens were inspected visually for cracking and evidence of distress after each load increment. Crack widths were measured and recorded after initial cracking, and before and after yielding of the longitudinal steel. Crack patterns were also recorded.

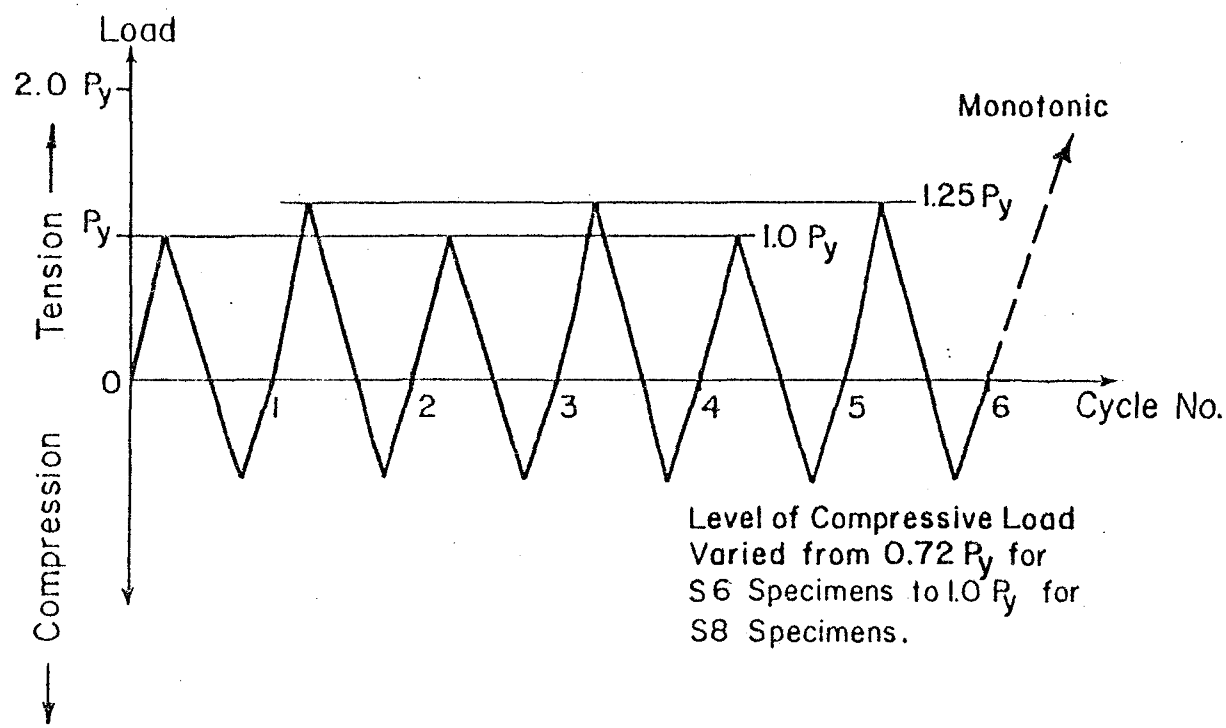


Fig. 7 Representative SR Loading History

OBSERVED BEHAVIOR

Amount and distribution of hoop reinforcement, and arrangement of longitudinal reinforcement were primary factors affecting observed strength, ductility and behavior. Capacity of the specimens was limited either by bar fracture or pull-out of spliced bars. Bar fracture occurred at the offset. Pull-out of spliced bars was associated with longitudinal splitting of the concrete.

A general discussion of force transfer mechanisms and effects of significant variables is presented in the following sections. Test results are summarized in Table 5. Detailed data for each specimen are given in Appendix B.

Force Transfer Mechanisms in Lap Splices

Forces between lapped bars in tension are transferred by bond stresses around the circumference of the bars. The bond stresses cause radial or "bursting" forces on the concrete surrounding the splice. These forces are concentrated at ends of the splice.(5)

Crack widths and strains measured in longitudinal and transverse reinforcement are shown in Figs. 8, 9, and 10. These figures are representative of all tests. They indicate the concentration of deformations and bursting forces at each end of the splice.

Strains in concrete and reinforcement were more heavily concentrated at the offset end of the splice than at the straight end. This resulted because the offset tended to "straighten

TABLE 5 - SUMMARY OF TESTS 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 parentheses indicates number of fully reversed cycles applied to the specimen prior to failure. 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

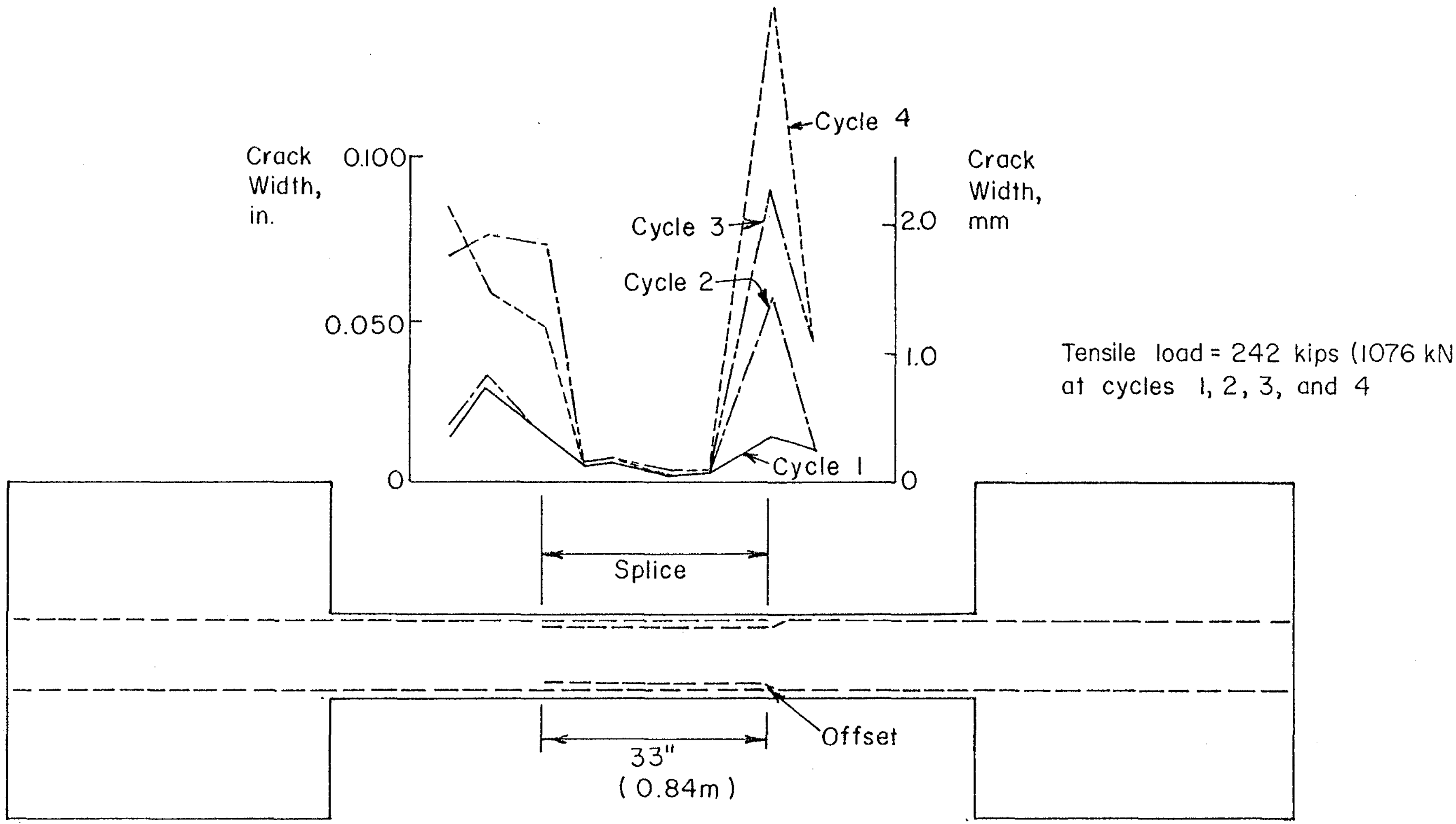


Fig. 8 Crack Widths Along Splice in Specimen S6-2

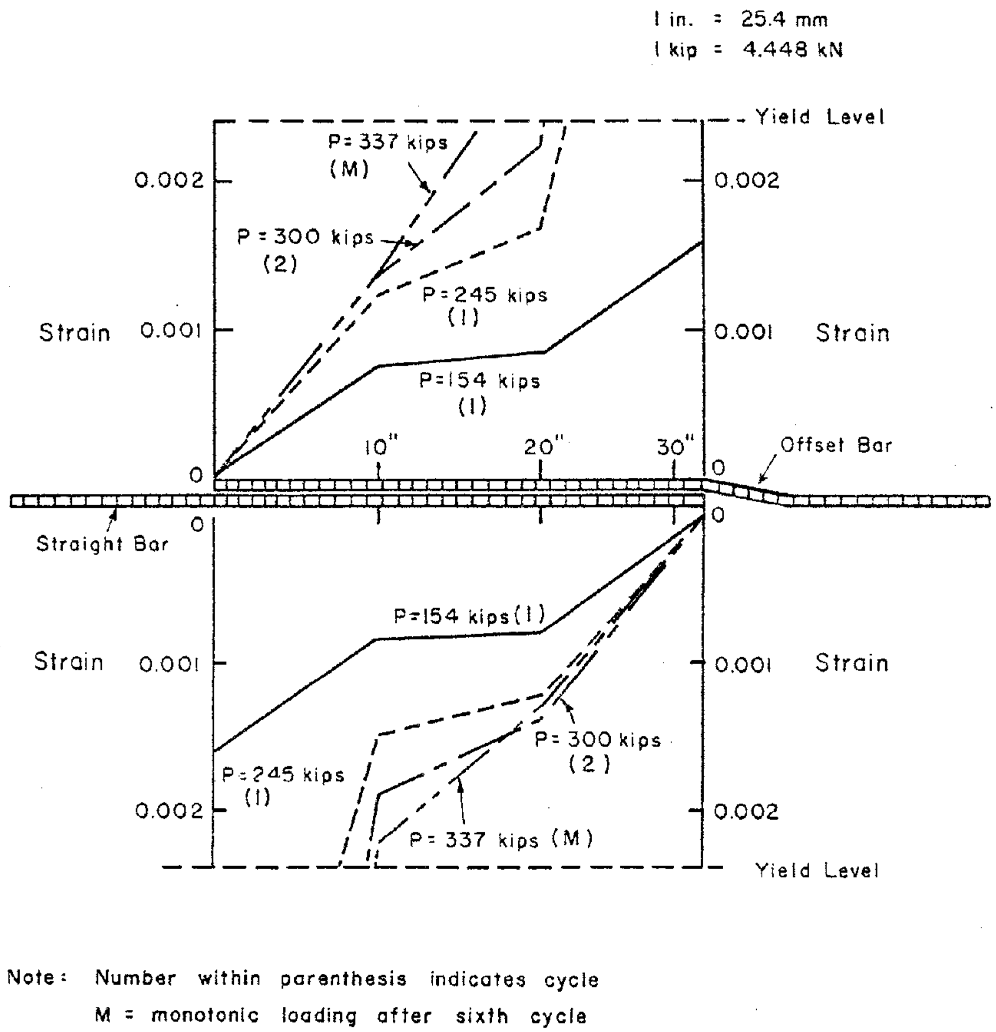


Fig. 9 Strains in Longitudinal Reinforcement of Specimen S6-2

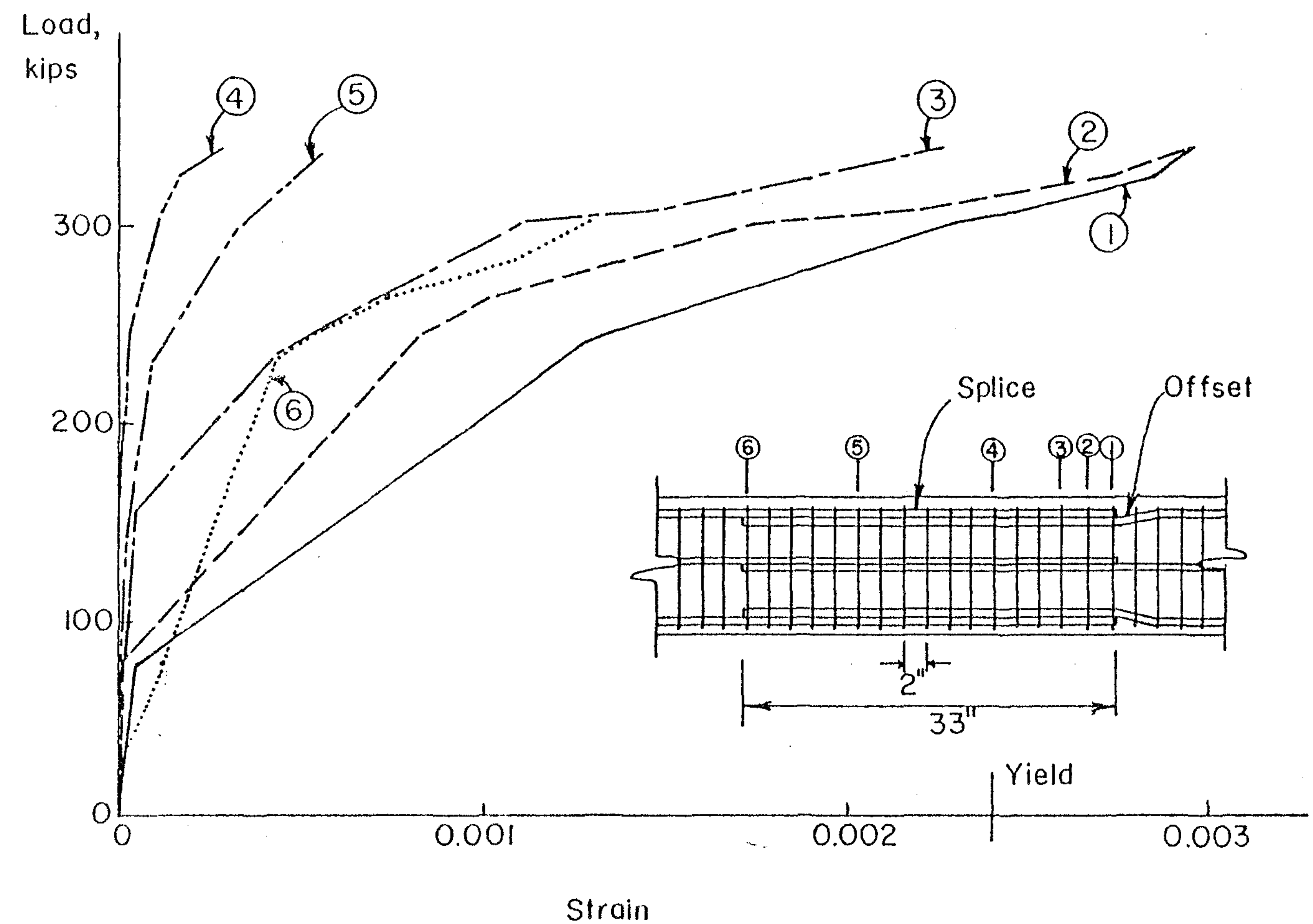


Fig. 10 Tensile Strains in Transverse Reinforcement in Specimen S6-2

out" when the longitudinal reinforcement was in tension. Therefore, an outward component of thrust was generated.

End bearing of bars at the offset also contributed to force transfer when longitudinal steel was in compression.

Severity and extent of bursting, and the load at which bursting occurred, depended on the relative size of the offset bars with respect to the size of the cross section. The amount and distribution of the transverse reinforcement was also a significant factor. Propagation of concrete spalling from end regions into the splice depended on the amount and distribution of the transverse reinforcement.

Bursting forces within the splice produced splitting cracks along the longitudinal lapped reinforcement. These forces were resisted by the transverse reinforcement. Some initial resistance was also obtained from concrete cover. Lap splices with very light transverse reinforcement failed violently with splitting propagating from the ends into the splice. Lap splices with heavy transverse reinforcement failed at the offset by bar fracture. Bar fracture was precipitated by pullout of interior bars.

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 the loading history shown in Fig. 7 did not vary significantly from that for specimens subjected to monotonic tensile loading.

Figure 11 shows load versus total elongation of nominally identical specimens subjected to different loading histories. The hysteresis loops correspond to specimens subjected to reversing loading and the broken lines correspond to companion monotonic tests. Results in Fig. 11 and Table 5 show that strength was not affected by the applied load history. However, final elongation was slightly affected by the applied load. Specimens subjected to monotonic loading had slightly larger ductilities than companion specimens subjected to load reversals.

All specimens except Specimen S8-4 attained a final strength larger than 1.25 times the calculated yield strength. Specimen S8-4 failed by bar fracture at the offset. One of the offset bars fractured during the first half of the fourth cycle.

Effects of Longitudinal Reinforcement

Amount and distribution of lapped reinforcement were important factors. 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.

Specimens tested in this program show effects of bar size and bar configuration. The 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

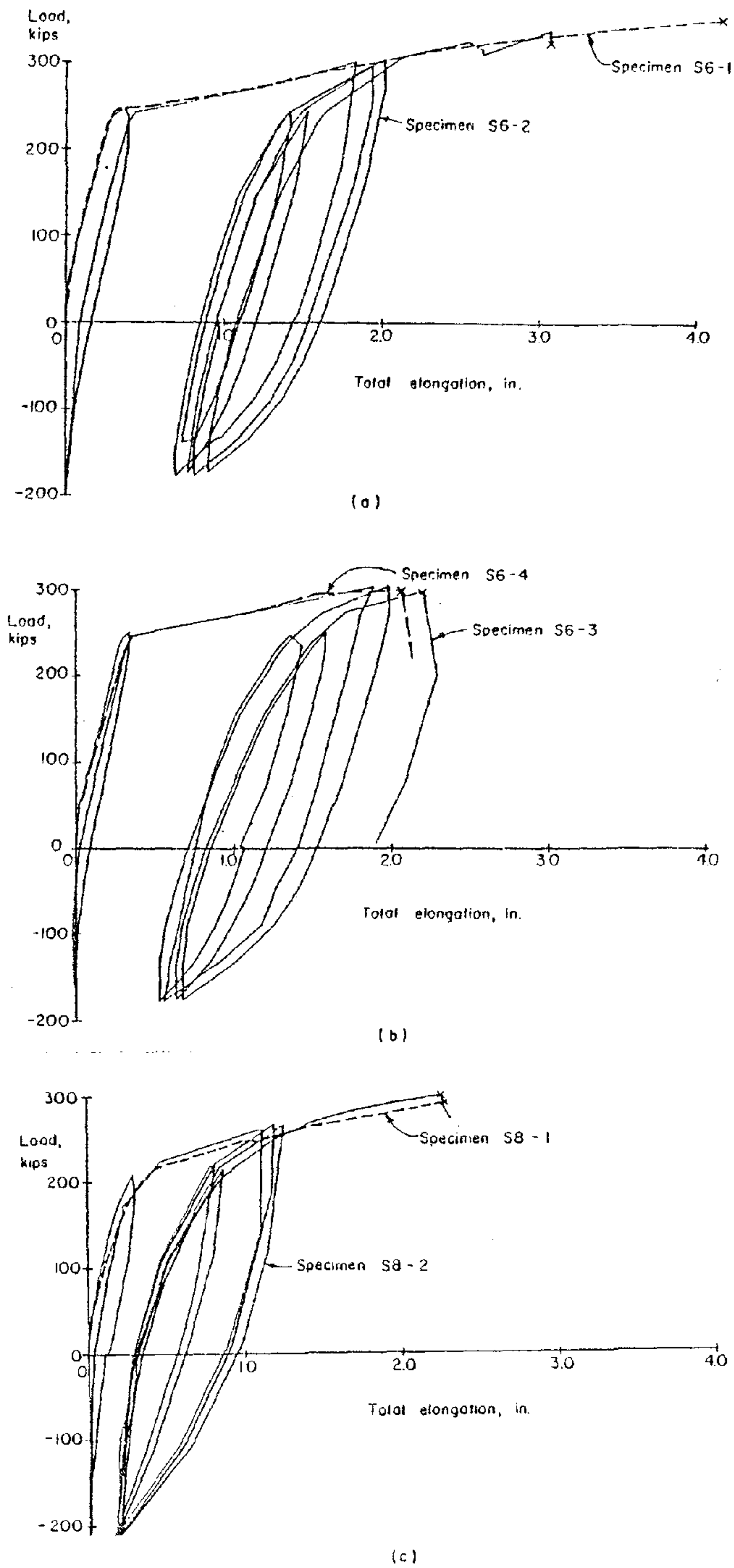


Fig. 11 Effects of Load Reversals

to the cross section. Figure 4 shows the reinforcement in S8 and S6 Specimens.

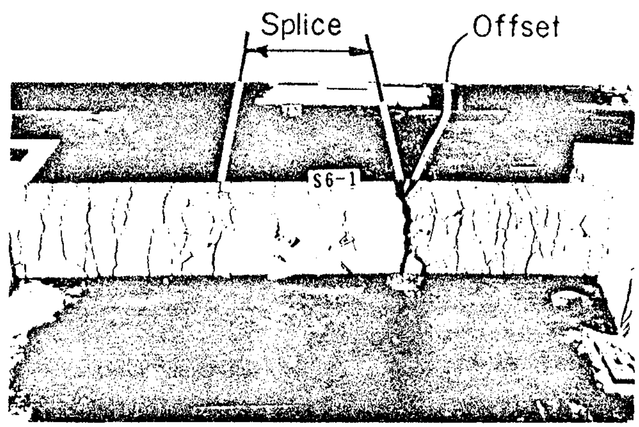
Figure 12 shows Specimens S6-1 and S8-1 after testing. Failure in S8 Specimens occurred at the offset except for Specimen S8-3 which had very light transverse reinforcement. The extent of bursting at the offset was more severe in S8 Specimens than in S6 Specimens.

Failure in S6 Specimens, except for Specimen S6-2, was initiated 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. As loads approached ultimate, interior spliced bars slipped, and load was transferred to corner bars which fractured. Longitudinal splitting was not as well contained for the interior bars as it was for the corner bars, which were confined within corners of transverse hoops.

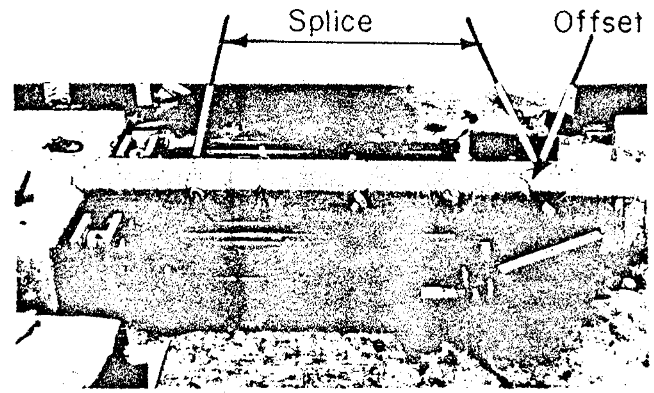
Effects of Transverse Reinforcement

Amount and distribution of transverse reinforcement were critical to ductility, strength and behavior. Transverse reinforcement controlled longitudinal splitting and bar slip as well as yield penetration along the spliced reinforcement. In particular, longitudinal lapped bars located within corners of hoops had less tendency to slip.

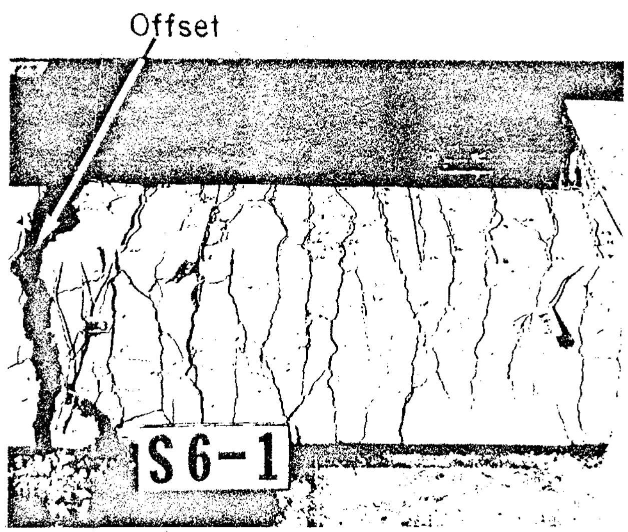
Figures 9 and 10 show strains in the longitudinal and transverse reinforcement along a splice. Intensity of strains at



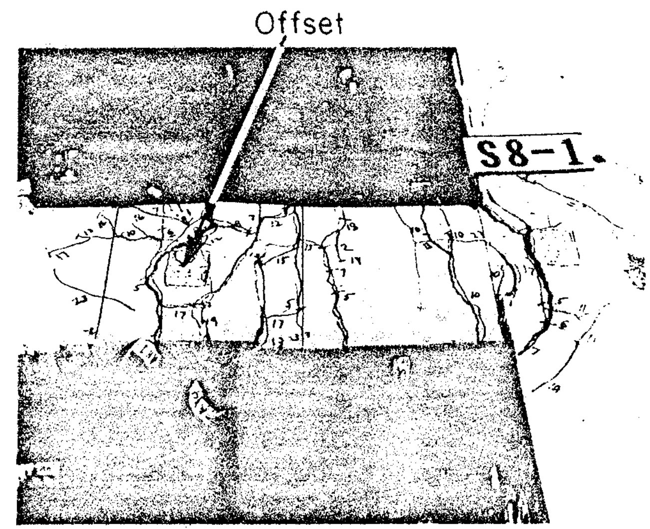
(a) Overall View - Specimen S6-1



(b) Overall View - Specimen S8-1



(c) Offset Region - Specimen S6-1



(d) Offset Region - Specimen S8-1

Fig. 12 Specimens S6-1 and S8-1 After Testing

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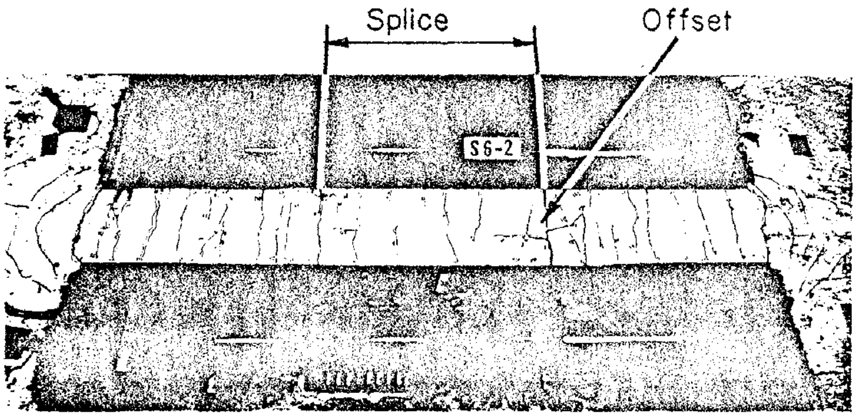
end regions of the splice indicated that location of transverse reinforcement is a critical factor. It appears that closely spaced hoops at the ends of a splice would improve ductility and performance. Concentration of hoops at the ends would contain splitting and loss of bond.

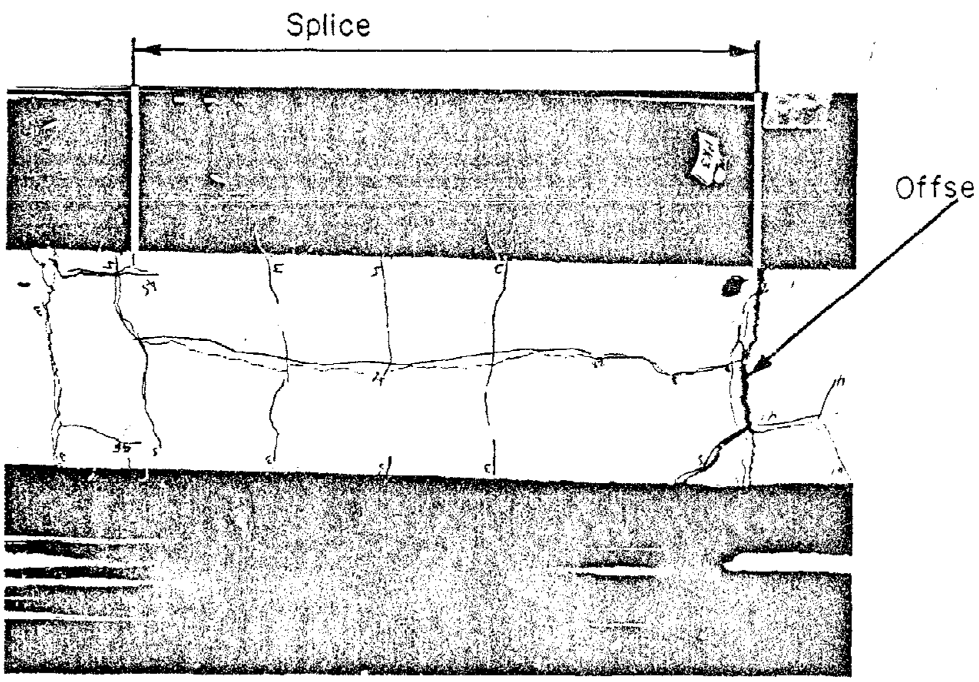
For the amounts of transverse reinforcement used in the tests, reduction in the number of uniformly distributed hoops caused only a slight reduction in load carrying capacity of the tension lap splice. Comparison of Specimens S6-2 and S6-3 in Table 5 shows that a 50% reduction in transverse reinforcement required by the UBC Code for seismic conditions 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.

Although reduction in transverse reinforcement did not significantly affect strength, it did affect behavior and ductility. Figure 13 shows Specimens S6-2 and S6-3 after testing. Specimen S6-2, which had 100% of the required transverse reinforcement, failed by bar fracture at the offset. Specimen S6-3, which had 50% of the required transverse reinforcement, failed by slip of the inner bars. The corner bars fractured after the inner bars pulled out.



(a) Specimen S6-2



(b) Specimen S6-3

Fig. 13 Specimens S6-2 and S6-3 After Testing

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Figures 14 and 15 show Specimens S8-1 and S8-3 after testing. Specimen S8-1, which had 100% of the required transverse reinforcement, failed by bar fracture. Specimen S8-3, which had 17% of the required seismic confinement reinforcement, failed by slip of the lapped reinforcement. Longitudinal bars pulled out at the straight end of the splice. Figures 13, 14, and 15 show that the extent of damage in S6 Specimens was not as severe as that in S8 Specimens, particularly at the offset end.

Figure 16a shows applied axial load versus total elongation envelope for Specimens S6-2 and S6-3. As expected, Specimen S6-2, which had 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. 16b, and Specimens S8-2 and S8-4, as shown in Fig. 16c.

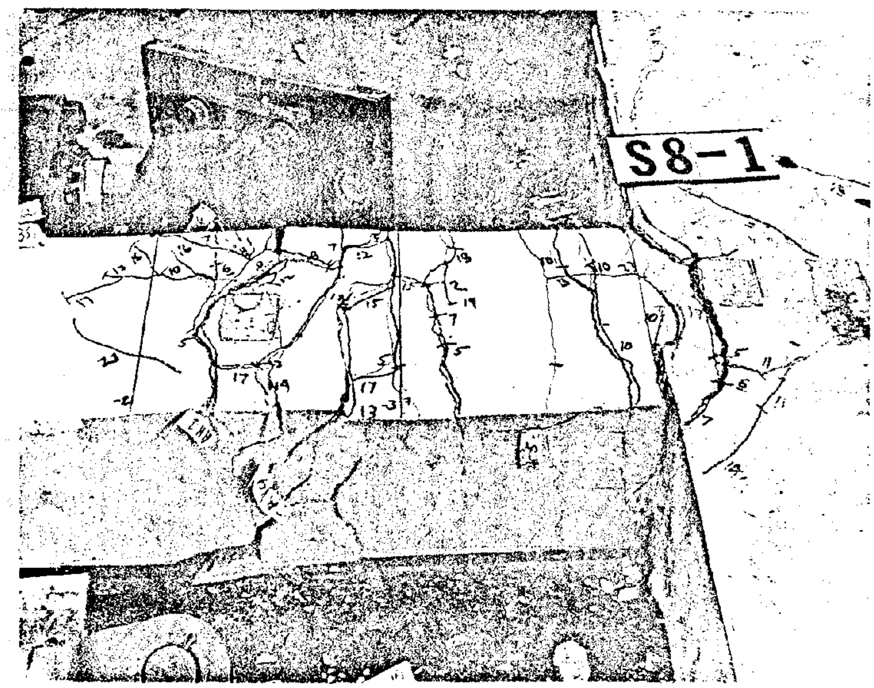

Fig. 14 Specimen S8-1 After Testing

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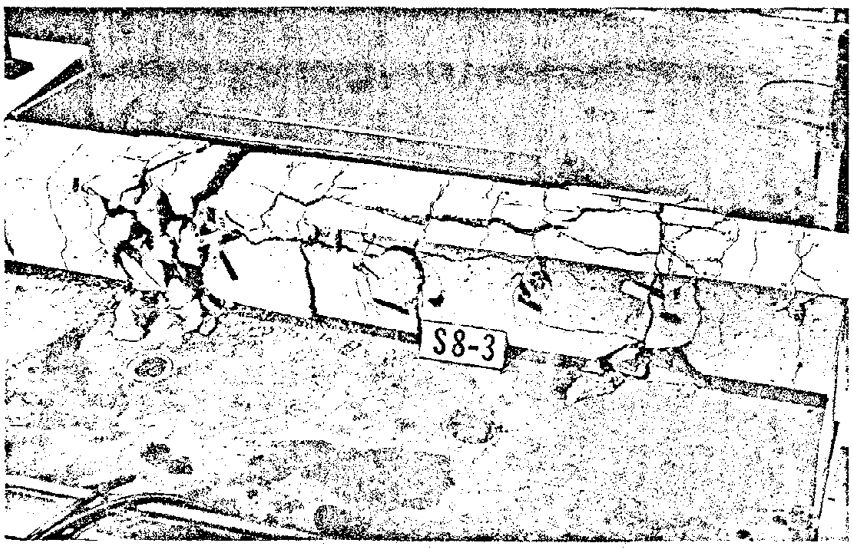

Fig. 15 Specimen S8-3 After Testing

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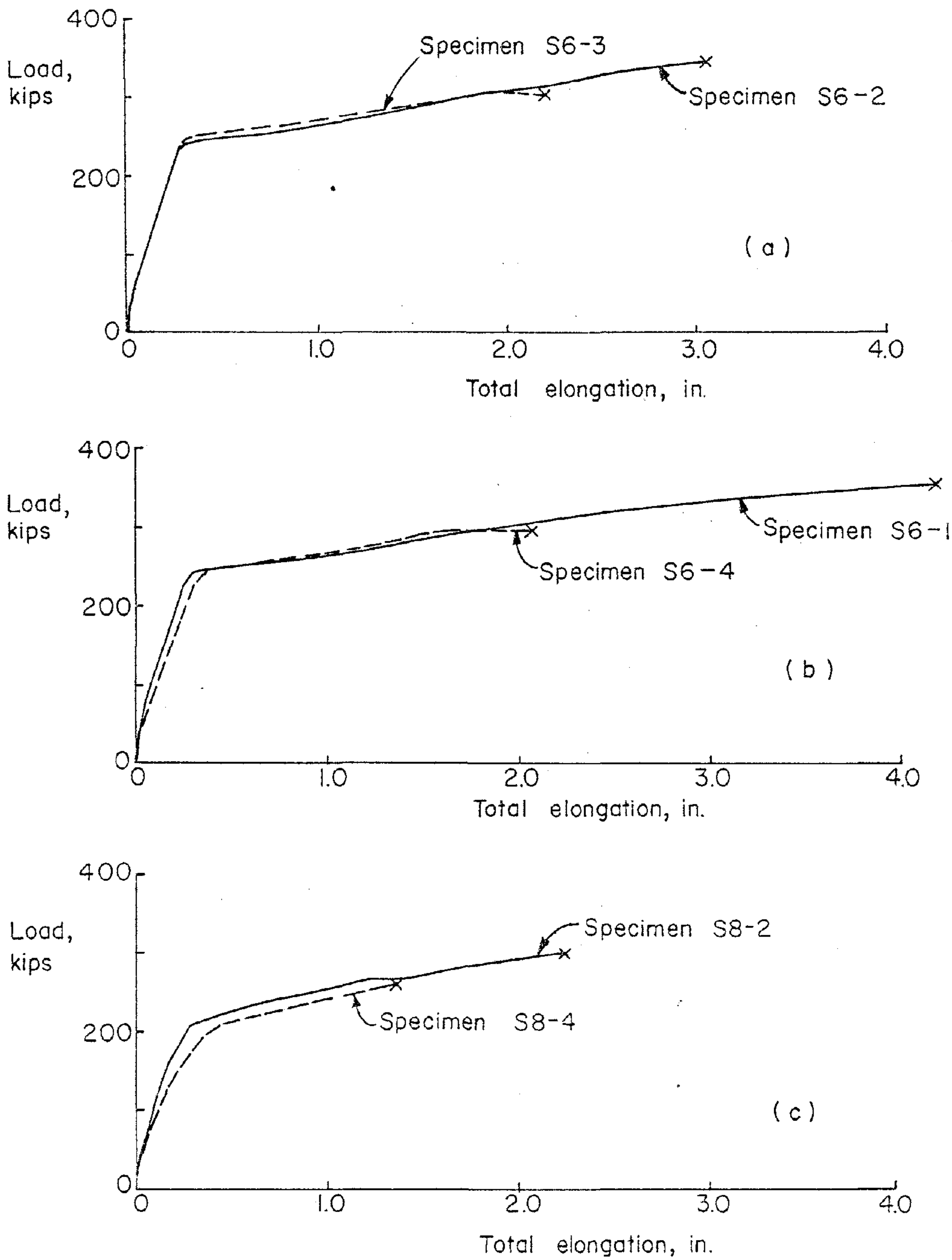

Fig. 16 Effects of Transverse Reinforcement

SUMMARY AND CONCLUSIONS

This report describes results of a test program to evaluate effectiveness of tension lap splices under inelastic stress reversals. Results of eight tests are included.

Variables considered were amount and configuration of lapped reinforcement, amount of transverse reinforcement, and load history.

Specimens were designed as Class C tension lap splices according to the 1977 ACI Building Code.(1) Lapped reinforcement included No. 6 and No. 8 bars. Specimens with No. 6 and No. 8 bars were termed S6 Specimens and S8 Specimens, respectively. Four specimens of each series were built and tested. In each case 100% of the reinforcement was spliced at the same location.

Following common practice, lapped bars were offset at one end of the lap over a length equal to six times the bar diameter. The amount of transverse reinforcement varied from that required for seismic design conditions to maximum column tie spacing. Four tests under tensile monotonic loading and four tests under reversing loading were made. Reinforcement with a nominal yield of 60,000 psi (414 MPa) and concrete with a nominal compressive strength of 3,000 psi (20.7 MPa) were used in design of the specimens.

Tests were performed on column elements that had cross-sectional dimensions of 12x12 in. (305 x 305 mm) and a length of 96 in. (2.44 m). Axial loads were applied to the column through two end blocks using hydraulic rams. Series S6 Specimens had eight No. 6 bars with a 33 in. (0.84 m) lap splice. Series S8 Specimens had four No. 8 bars with a 60 in. (1.52 m) lap.

Specimens were instrumented to measure loads, axial elongations, crack widths, and longitudinal and transverse steel strains.

The following observations are based on the eight tests:

(1) Specimens designed as Class C lap splices with transverse reinforcement for seismic conditions according to the 1976 UBC Code[2] performed very well under monotonic and reversing loads. Strength of these specimens varied from 92% to 94% of average tensile strength of the longitudinal reinforcement. Strengths varied from 169% to 174% of the design yield load.

(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 ductility than those subjected to load reversals.

(4) The 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 failure in the reinforcement in structures under reversing loads.

(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. They were first observed as the load approached yield. As the tensile load approached ultimate, interior spliced bars slipped and transferred load to the 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) The amount and distribution of transverse reinforcement have a critical effect on ductility, strength and behavior of lap splices. An insufficient amount of hoop reinforcement at the ends of a splice can lead to reduction in ductility and strength, and to severe damage within the splice region. From measurements of strains in transverse reinforcement, it appears that closely spaced hoops at the ends of a splice would improve performance. Hoops at the ends of the splice were more effective than interior hoops in resisting splitting and bursting of the concrete.

(8) If the design criteria for lap splices is strength, the 1976 UBC Code requirements for confinement in seismic regions are conservative with regard to amount

of transverse reinforcement around the splices. In S8 Specimens, which had a four corner bar arrangement, a reduction of 83% in the required transverse reinforcement caused a reduction of only 15% in strength. In S6 Specimens, which had an eight bar arrangement, a reduction of 50% in the required transverse reinforcement caused a reduction of 15% in strength.

(9) Transverse hoops must be in contact with longitudinal bars to be effective.

ACKNOWLEDGMENTS

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J. Julien assisted with preparation of the manuscript. E. M. Ringquist provided editorial assistance.

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APPENDIX B - TEST RESULTS

In this section results for each test are presented in detail. Specimen behavior during testing is described and supporting data are presented.

The following results are included:

a. Load vs. axial elongations

b. Crack patterns and distribution of crack widths.

c. Load vs. strain, and strain distribution along longitudinal reinforcement.

d. Load vs. strain of transverse reinforcement.

The test program and results are summarized in Tables 2 and 5, of the main text.

S6 Specimens

Four Specimens S6-1, S6-2, S6-3, and S6-4 were built using No. 6 bars as longitudinal reinforcement. Controlled variables included type of loading and amount of transverse reinforcement. Specimens S6-1 and S6-4, tested under monotonic loading, were companions to Specimens S6-2 and S6-3, which were tested under load reversals.

Specimens S6-1, S6-2, S6-3, and S6-4 differed in amount of lateral reinforcement. Specimens S6-1 and S6-2 were built with confinement according to seismic provisions of the 1976 Uniform Building Code.[2] To investigate effects of amount of transverse reinforcement, Specimens S6-3 and S6-4 were built with 50% of the code required transverse reinforcement.

Details of specimens are given in Fig. 4b and Table 2. The splice length was 33 in. (0.84 m). Material properties are summarized in Tables 3 and 4. Calculated and observed yield, and maximum loads and modes of failure, are summarized in Table 5.

Specimen S6-1

Plots of load versus elongation are shown in Fig. B-1. Initial and final crack patterns are shown in Fig. B-2.

Cracking was first observed at a load of 47 kips (209 kN). Distribution of initial cracks was uniform over the column portion of the specimen. As loading progressed, cracks at the ends of the lap were observed to grow wider than those at other locations. Widest cracks were observed at the location of the offset. Measured crack widths are presented in Fig. B-3.

Initial yielding of the longitudinal reinforcement was indicated by strain gage measurements at a load of 225 kips (1001 kN). Full yielding was measured at 246 kips (1094 kN). This is evident in the load versus elongation curves shown in Fig. B-1.

Measured strains in the longitudinal reinforcement are plotted in Figs. B-4, B-5, and B-6. The plot of strains along corner bars, as shown in Fig. B-6, indicates a consistent "anti-symmetric" distribution along each bar in the splice. As load increased the strain distribution tended to become linear.

At a load of 200 kips (890 kN) spalling of concrete cover was observed at the offset as a result of bursting forces that developed. This was also evident from measured strains in

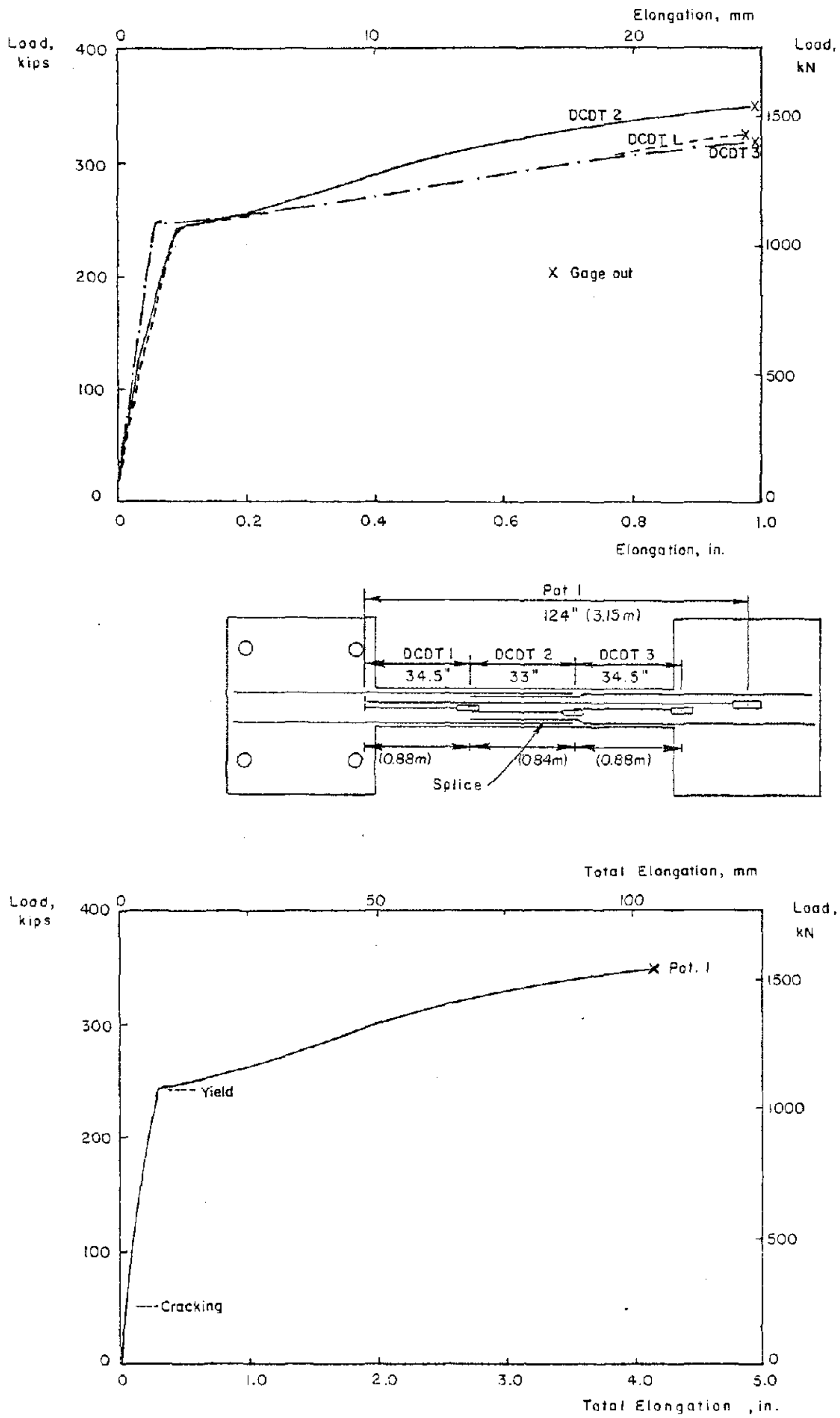
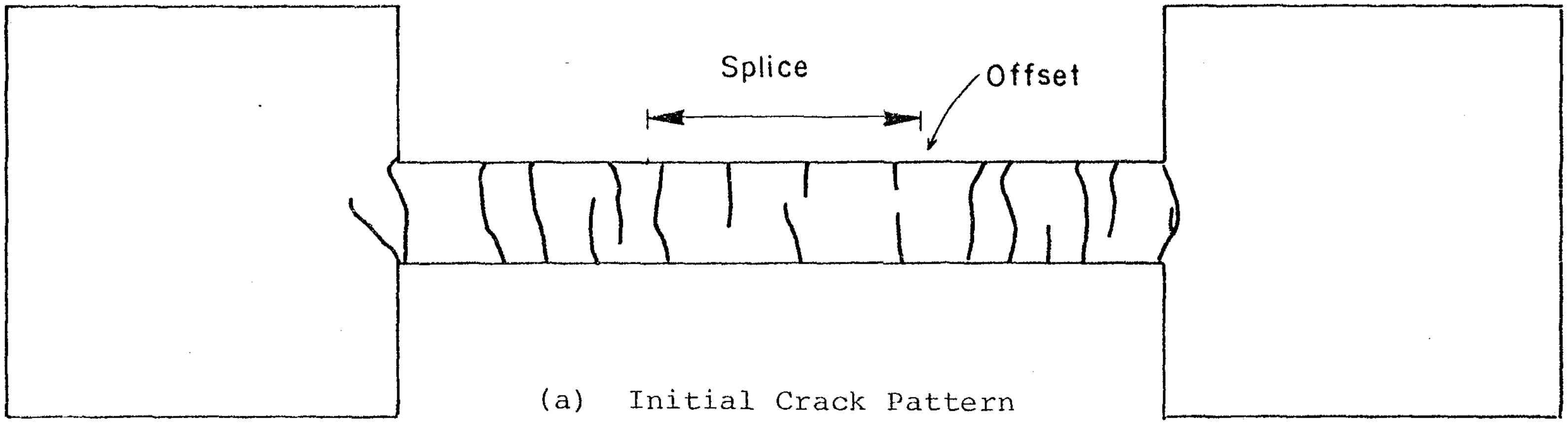
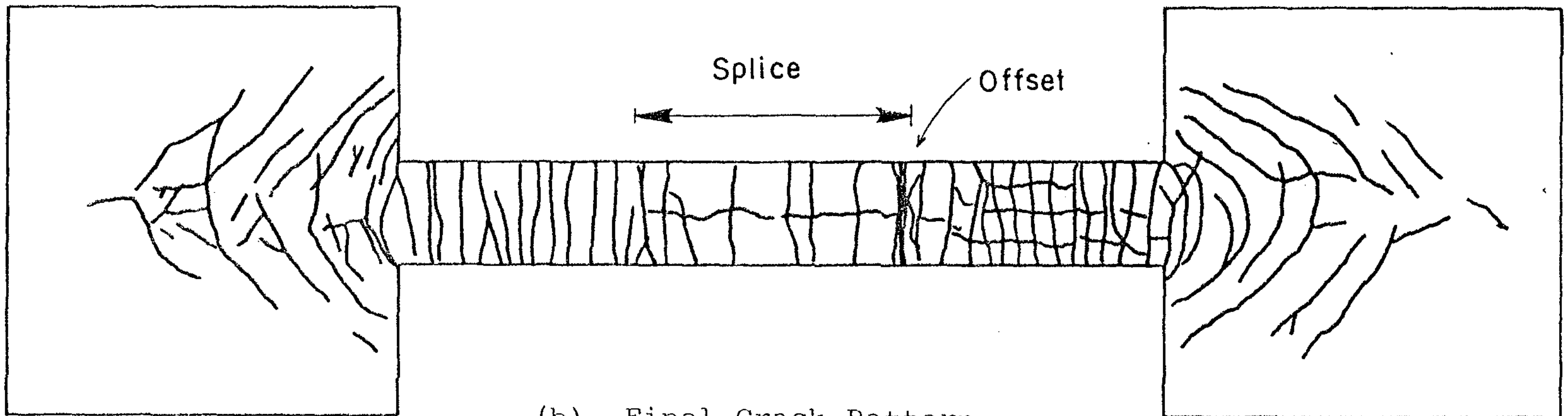


Fig. B-1 Axial Deformations of Specimen S6-1



(a) Initial Crack Pattern



(b) Final Crack Pattern

Fig. B-2 Crack Patterns of Specimen S6-1

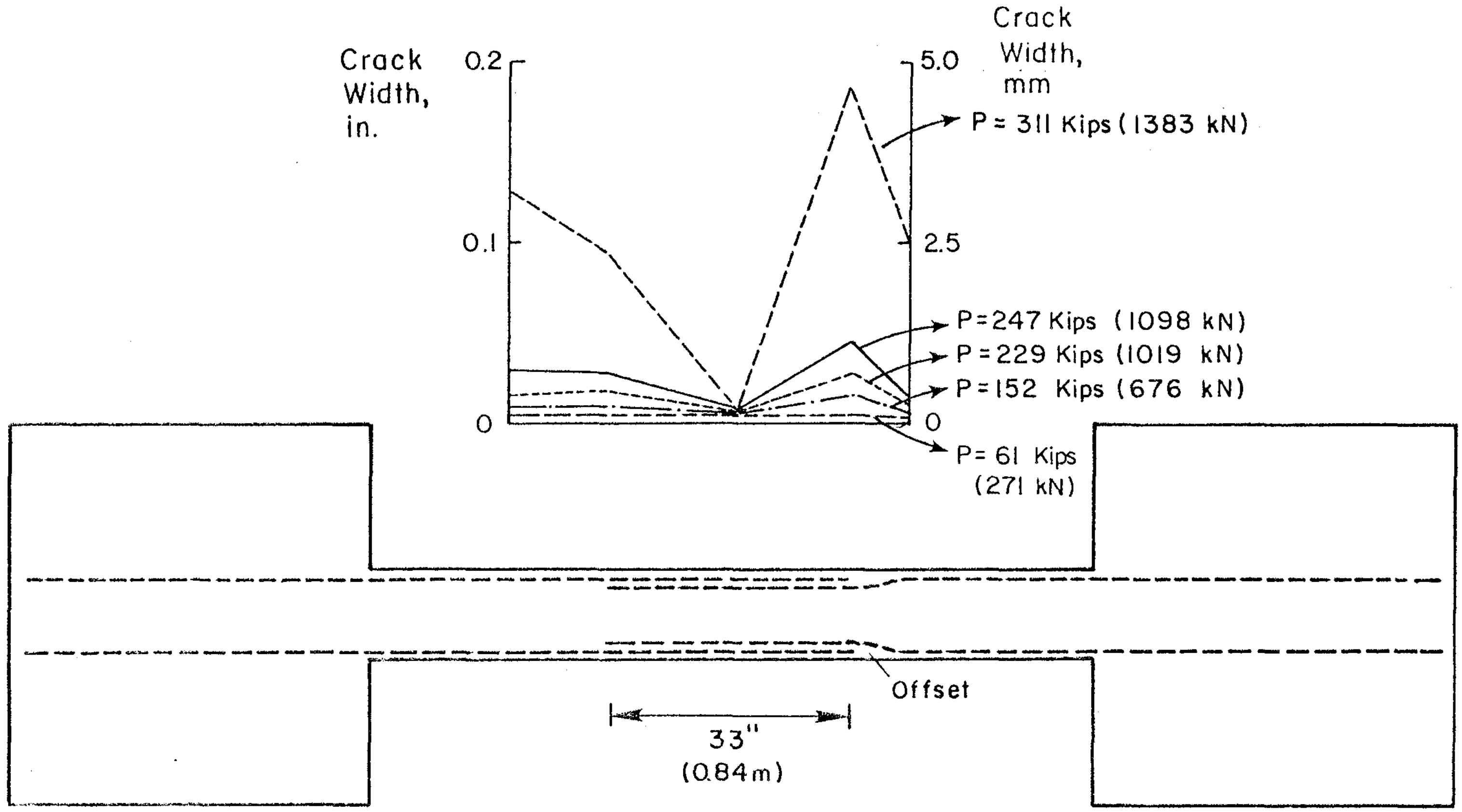


Fig. B-3 Measured Crack Widths in Specimen S6-1

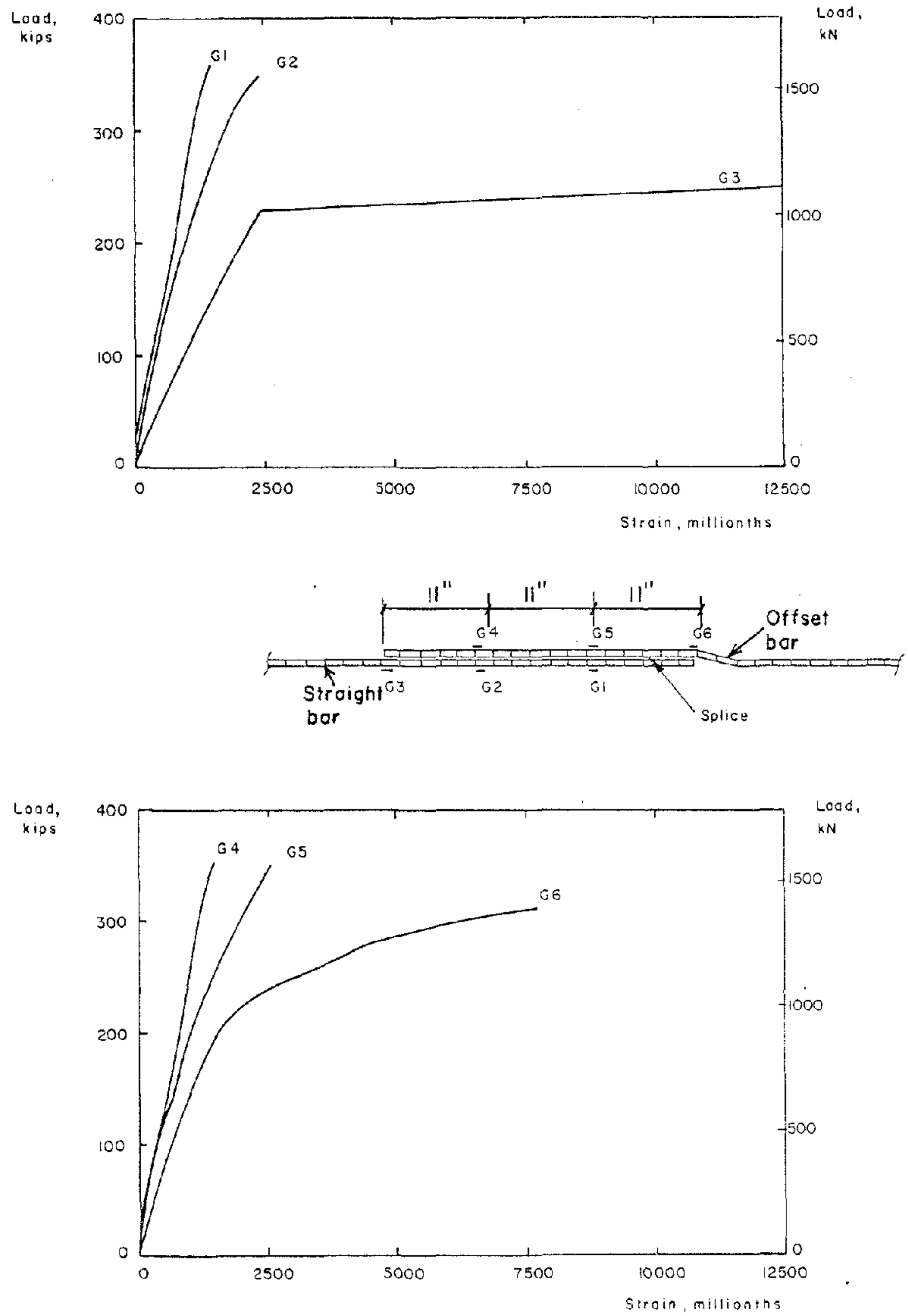


Fig. B-4 Load versus Steel Strains in Corner Bars for Specimen S6-1

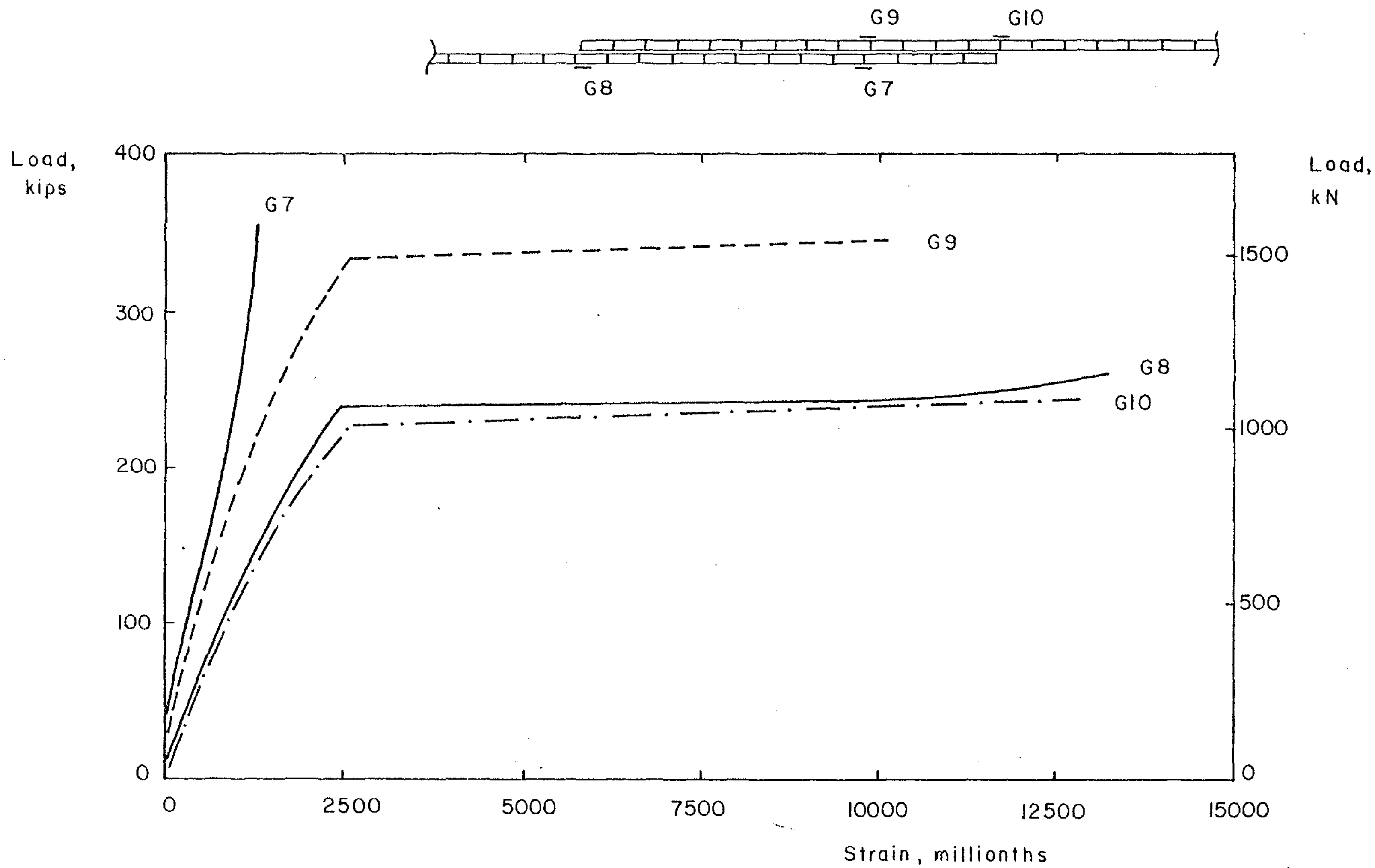


Fig. B-5 Load versus Steel Strains in Inner Bars for Specimen S6-1

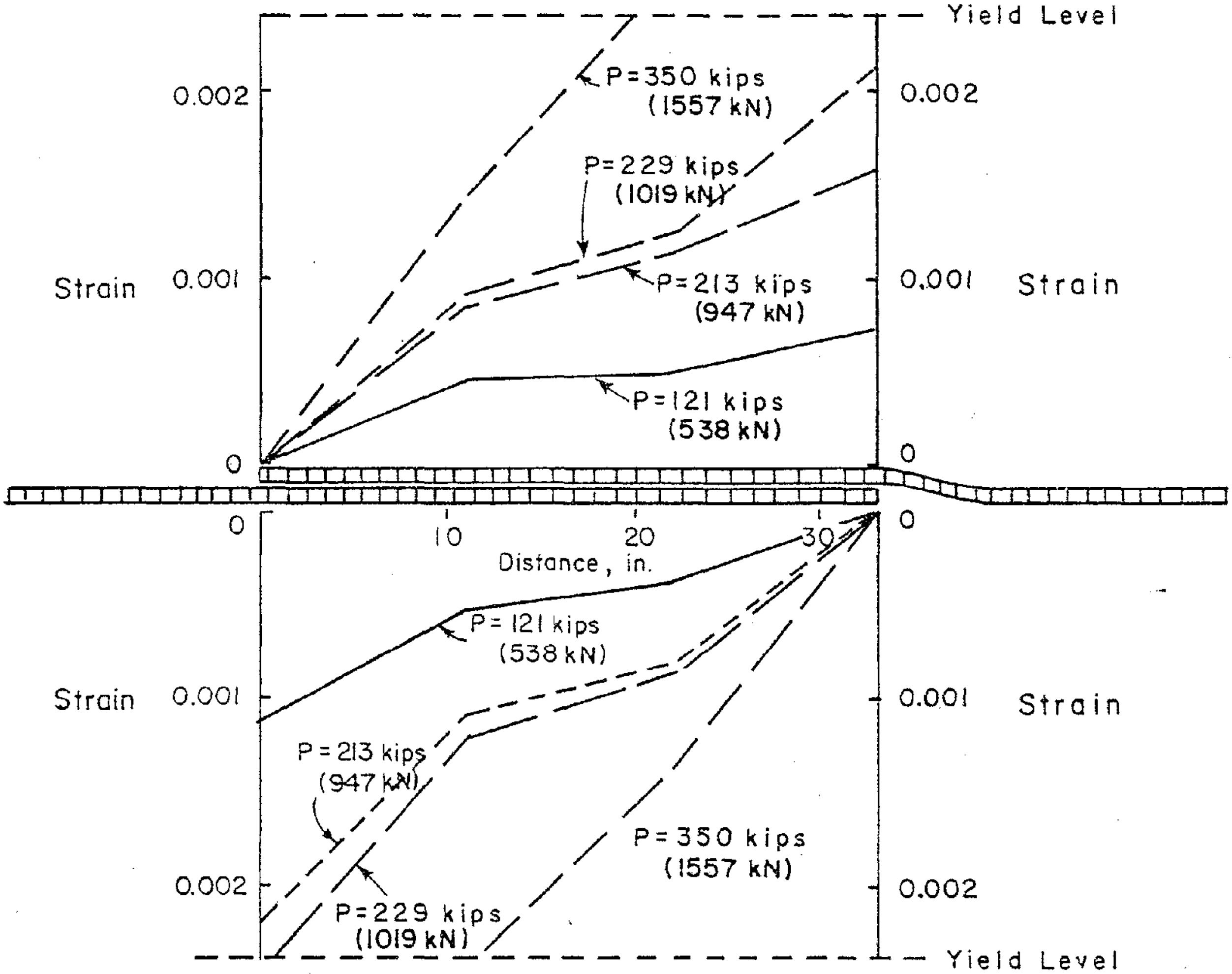


Fig. B-6 Strain Distribution Along Corner Splice of Specimen S6-1

transverse hoop reinforcement. Figure B-7 is a plot of applied load versus strains in selected hoops. Measured strains in Gage No. 2, on a hoop at the offset, indicate that this hoop was effective almost from the onset of loading. The hoop instrumented with Gage No. 1 was ineffective throughout the test. This hoop was not in contact with longitudinal reinforcement.

Significant longitudinal splitting cracks were observed at the ends of the splice and along the interior bars at a load of 326 kips (1450 kN). Hoop strains in Fig. B-7 indicate that transverse expansion began at an earlier load stage, but was not visually evident. As load approached ultimate, interior spliced bars slipped and transferred load to corner bars. At a load of 357 kips (1588 kN), corner bars fractured at the offset bend. It was apparent that longitudinal splitting was not as well contained for interior bars as it was for exterior bars. This is attributed to the fact that the exterior bars were located within the corners of transverse hoops.

The specimen reached a capacity equivalent to 94% of its calculated strength. Calculated yield and maximum loads, based on average reinforcement properties, are listed in Table 5.

<u>Specimen S6-2</u>

Plots of load versus elongation are shown in Fig. B-8. Initial and final crack patterns are shown in Fig. B-9.

Cracking was first observed at a load of 47 kips (209 kN). Initial cracking was uniform. Cracks at the ends of the splice were observed to grow wider than those at other locations.

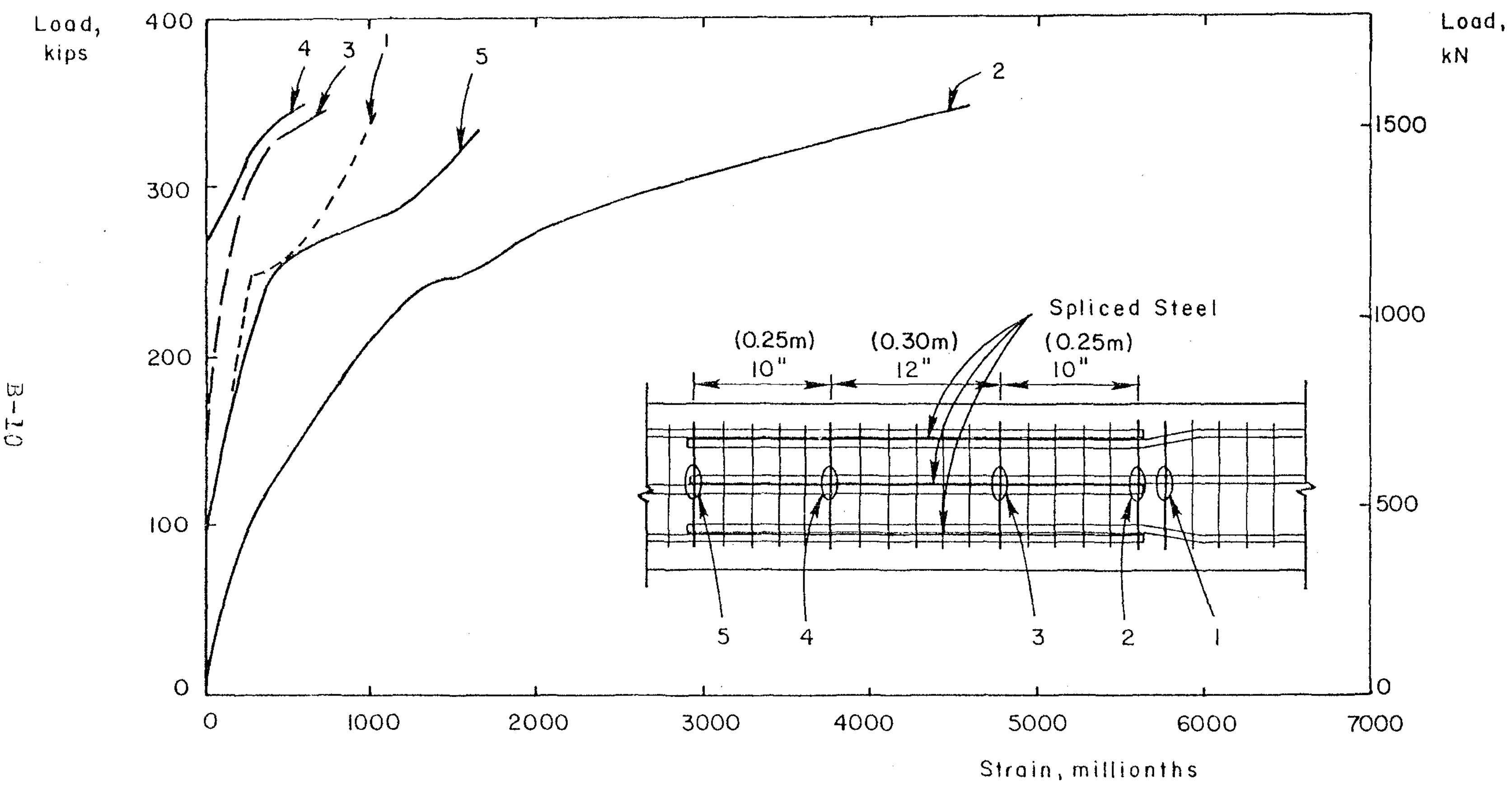


Fig. B-7 Load versus Hoop Strains for Specimen S6-1

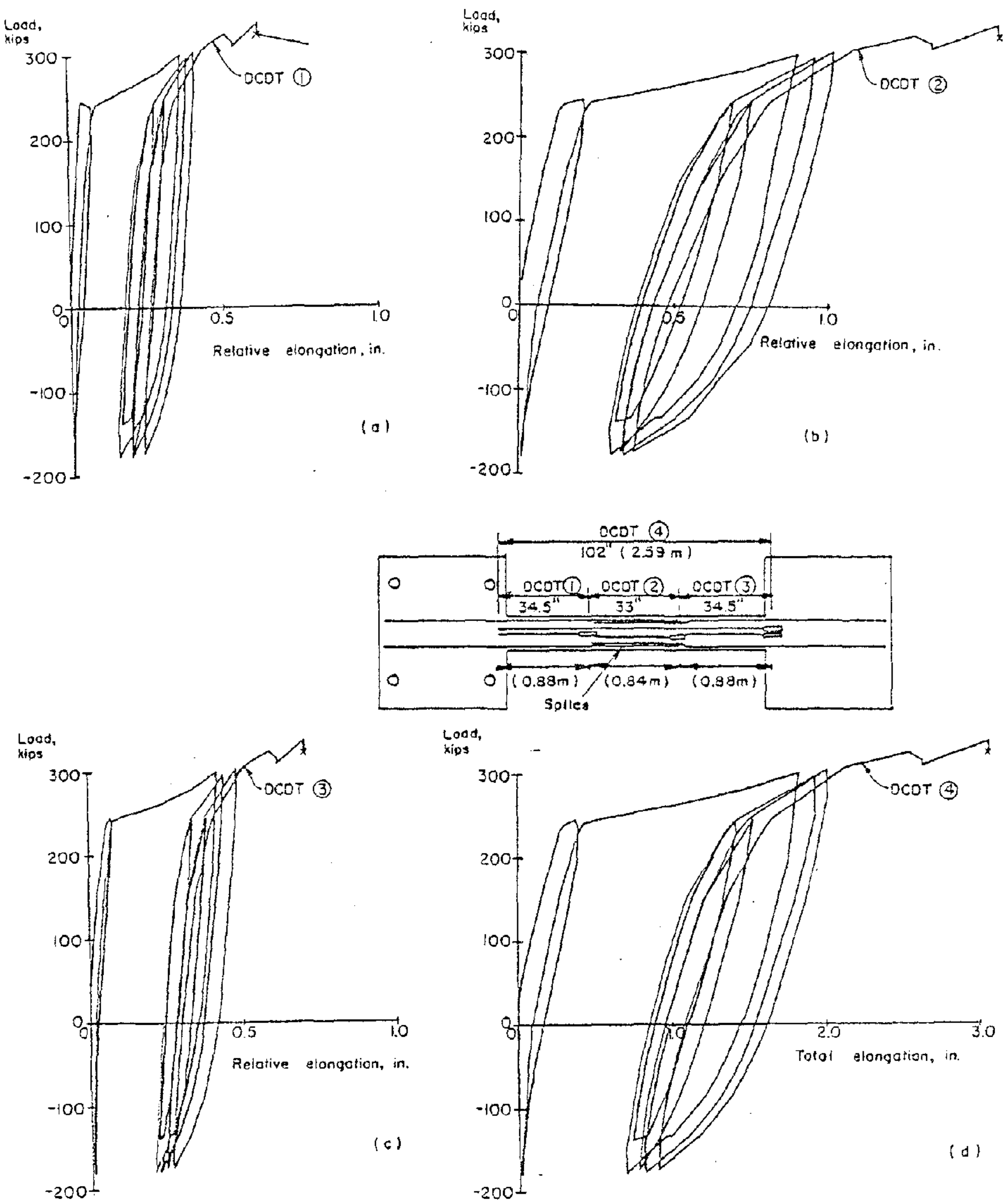
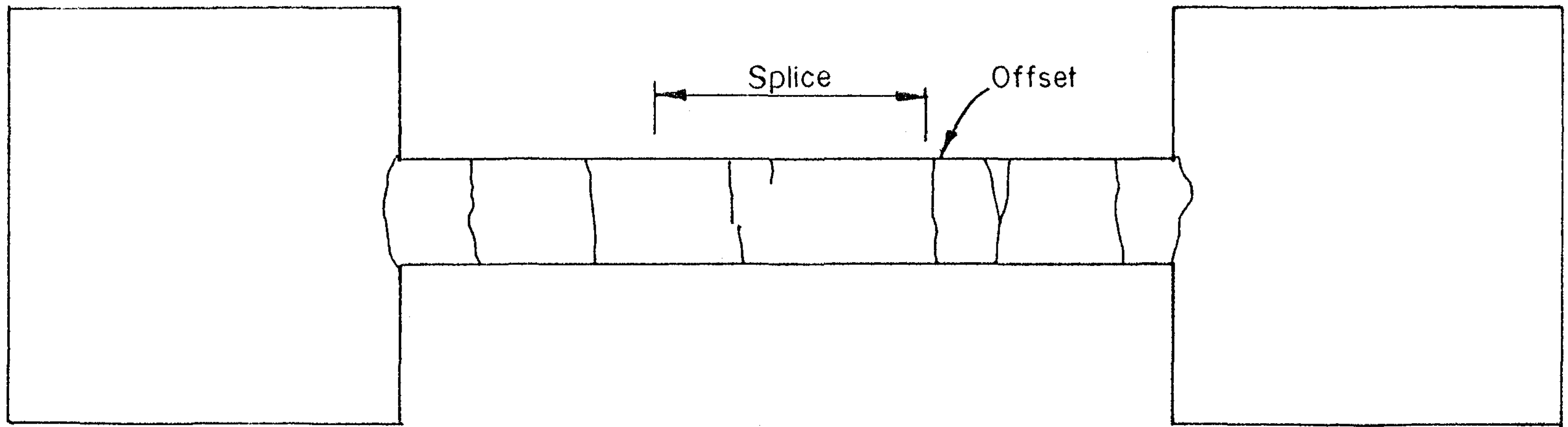
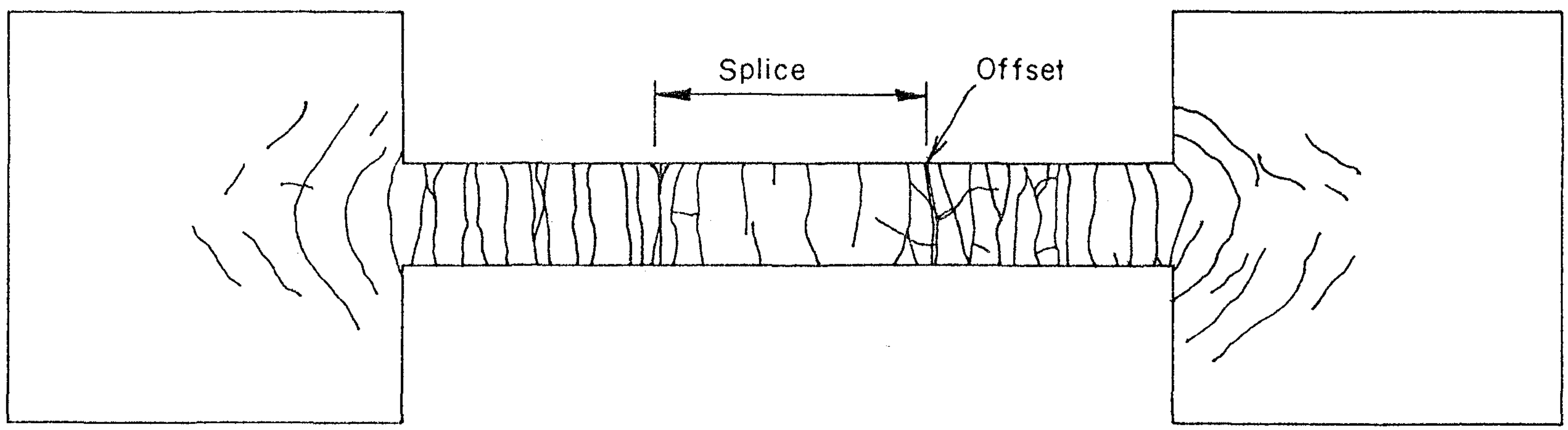


Fig. B-8 Axial Deformations of Specimen S6-2



(a) Initial crack pattern



(b) Final crack pattern

Fig. B-9 Crack Patterns of Specimen S6-2

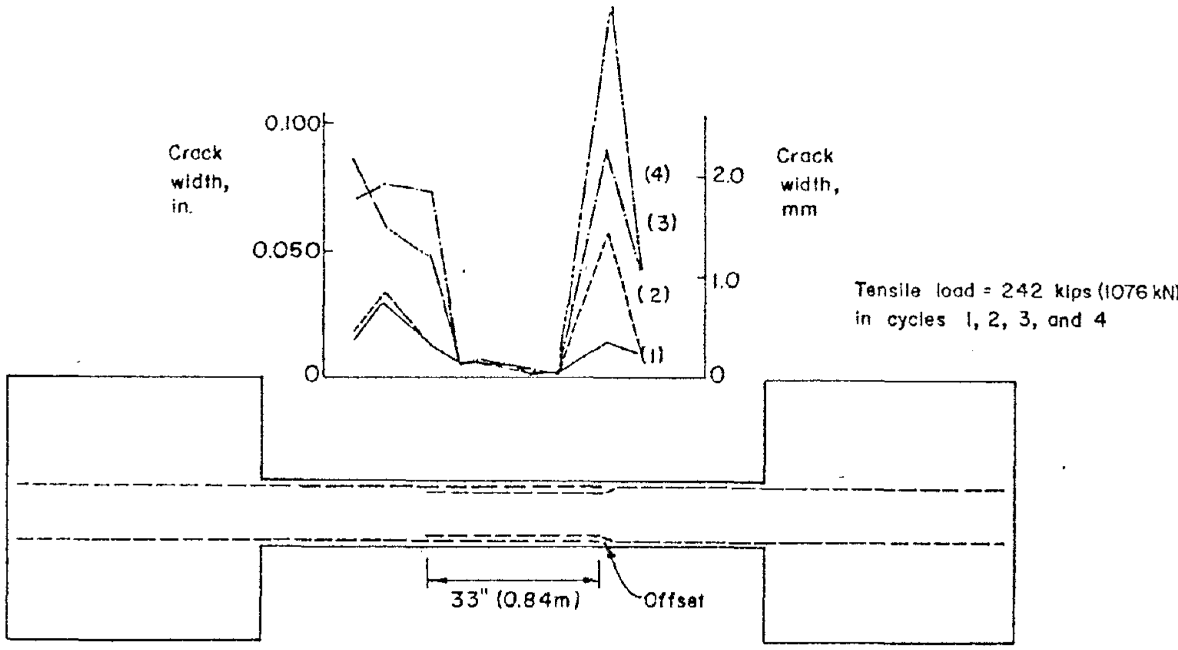
Figure B-10 shows crack widths at the peaks of tensile loading cycles. As expected, inelastic load reversals caused progressive permanent deformations and subsequent growth of the specimen.

Full yield load and ultimate strength were identical to those measured in monotonic test S6-1. Full yield load was 246 kips (1094 kN) and load capacity was 357 kips (1588 kN).

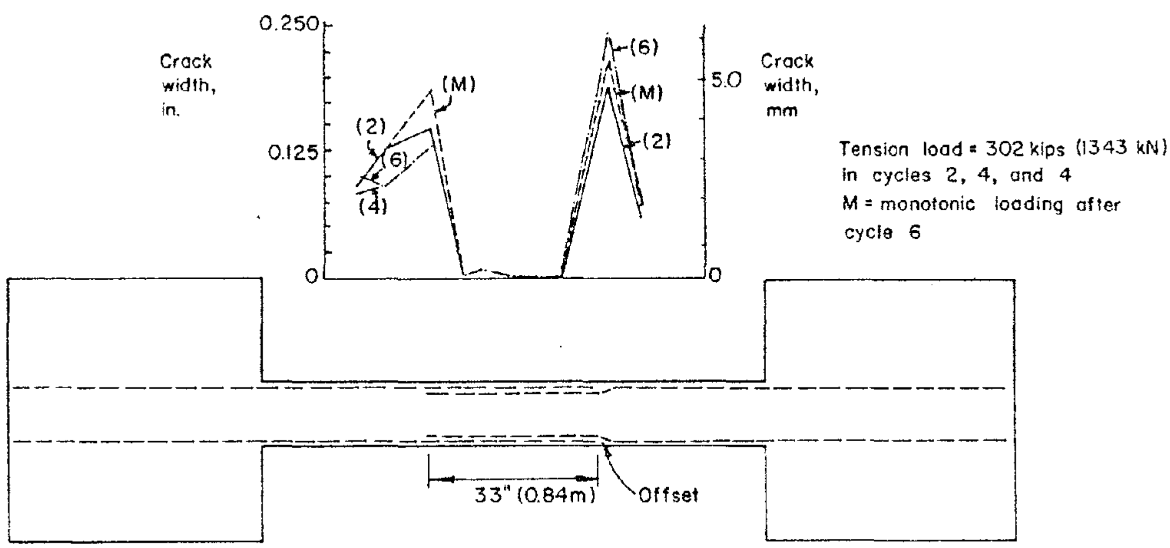
Measured strains in longitudinal reinforcement are shown in Figs. B-11, B-12, B-13, and B-14. Strains along the inner bars shown in Fig. B-14 indicate an "anti-symmetric" distribution along each bar in the splice. As tensile loads increased the strain distribution became linear. A similar strain distribution in the longitudinal reinforcement was observed in Specimen S6-1, as shown in Fig. B-6. Yield "penetration" within the lapped bars varied from 1/3 to 1/2 of the splice length.

Figures B-15 and B-16 show measured strains in transverse reinforcement. Strain readings in hoop No. 1, which was located at the edge of the offset, indicates that transverse expansion began from the first load stage. Strains in hoop Nos. 1, 2, and 3, which were at the offset end of the splice, indicate that these hoops were more effective than other hoops along the splice. The closer the hoop to the ends of the splice, the more effective it was, particularly at the offset end. This is clear from the sequence of yielding in the hoops. Hoops 1, 2, and 3 yielded as applied tensile load reached 307 kips (1366 kN), 314 kips (1397 kN), and 346 kips (1539 kN), respectively.

Strains in the hoop at the edge of the straight end of the splice indicated that this hoop was not as effective as those



(a) Tensile load = 242 kips (1076 kN)



(b) Tensile load = 302 kips (1343 kN)

Fig. B-10 Measured Crack Widths in Specimen S6-2

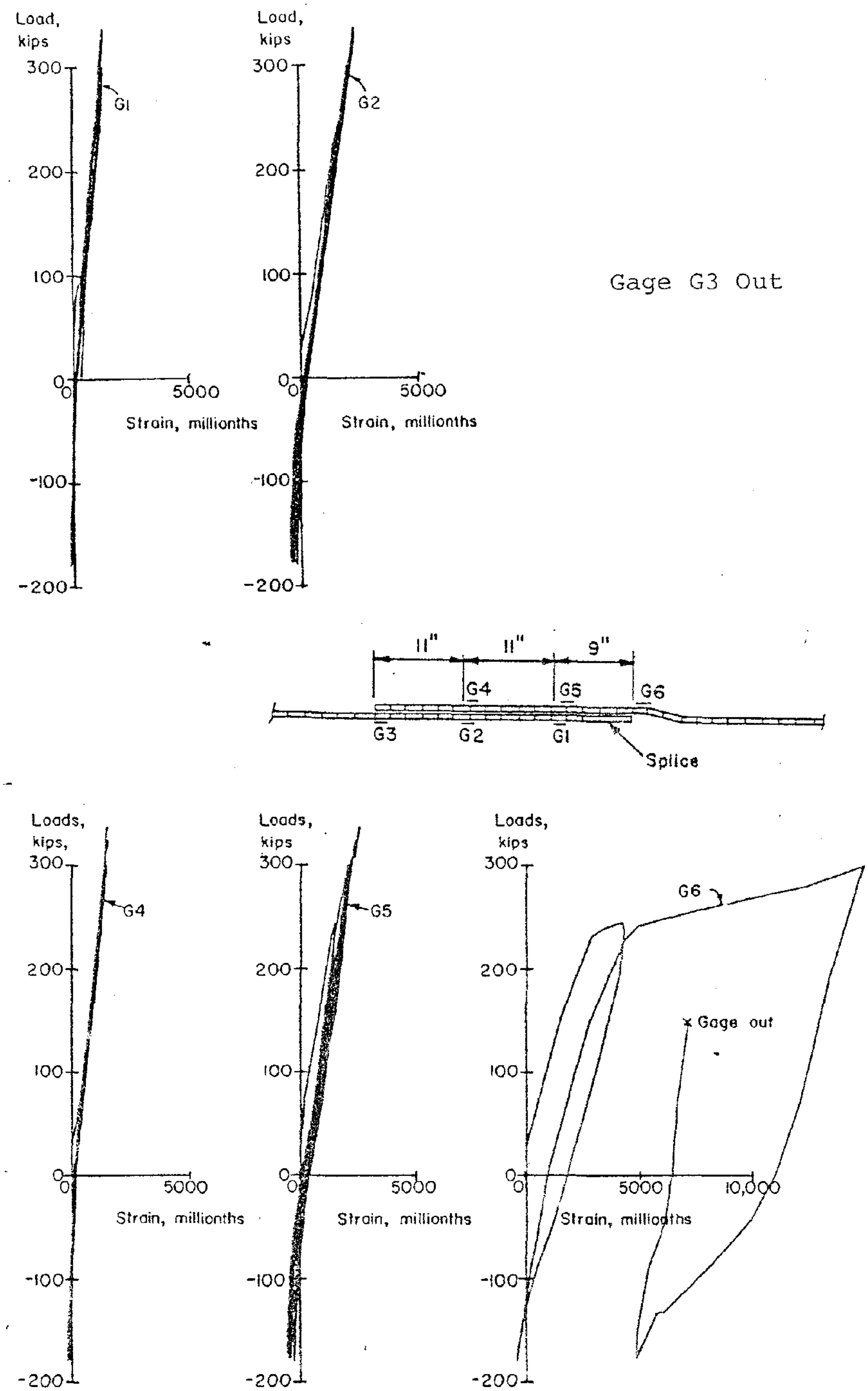


Fig. B-11 Load versus Steel Strains in Corner Bars for Specimen S6-2

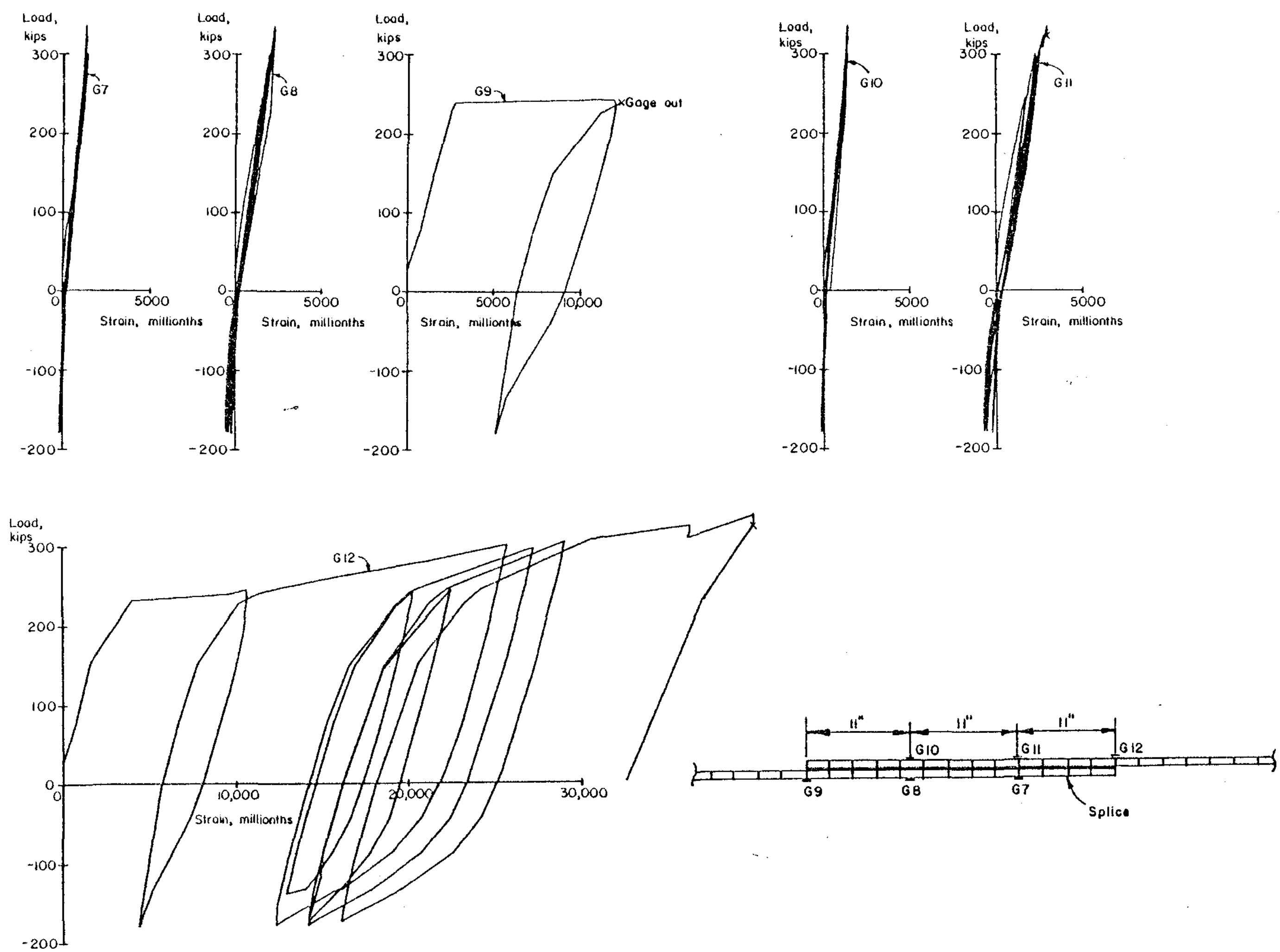


Fig. B-12 Load versus Steel Strains in Inner Bars for Specimen S6-2

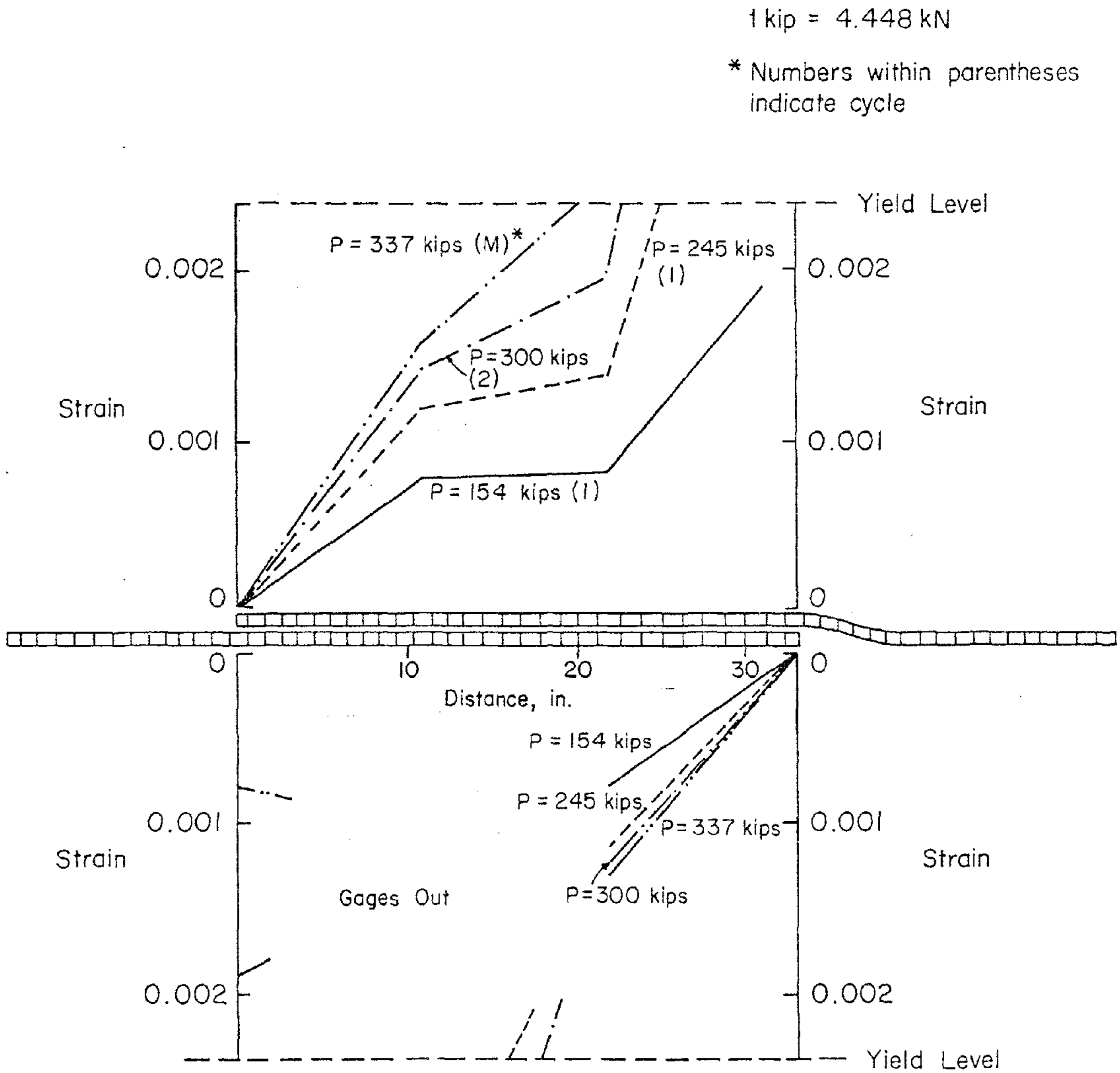


Fig. B-13 Strain Distribution Along Corner Splices of Specimen S6-2

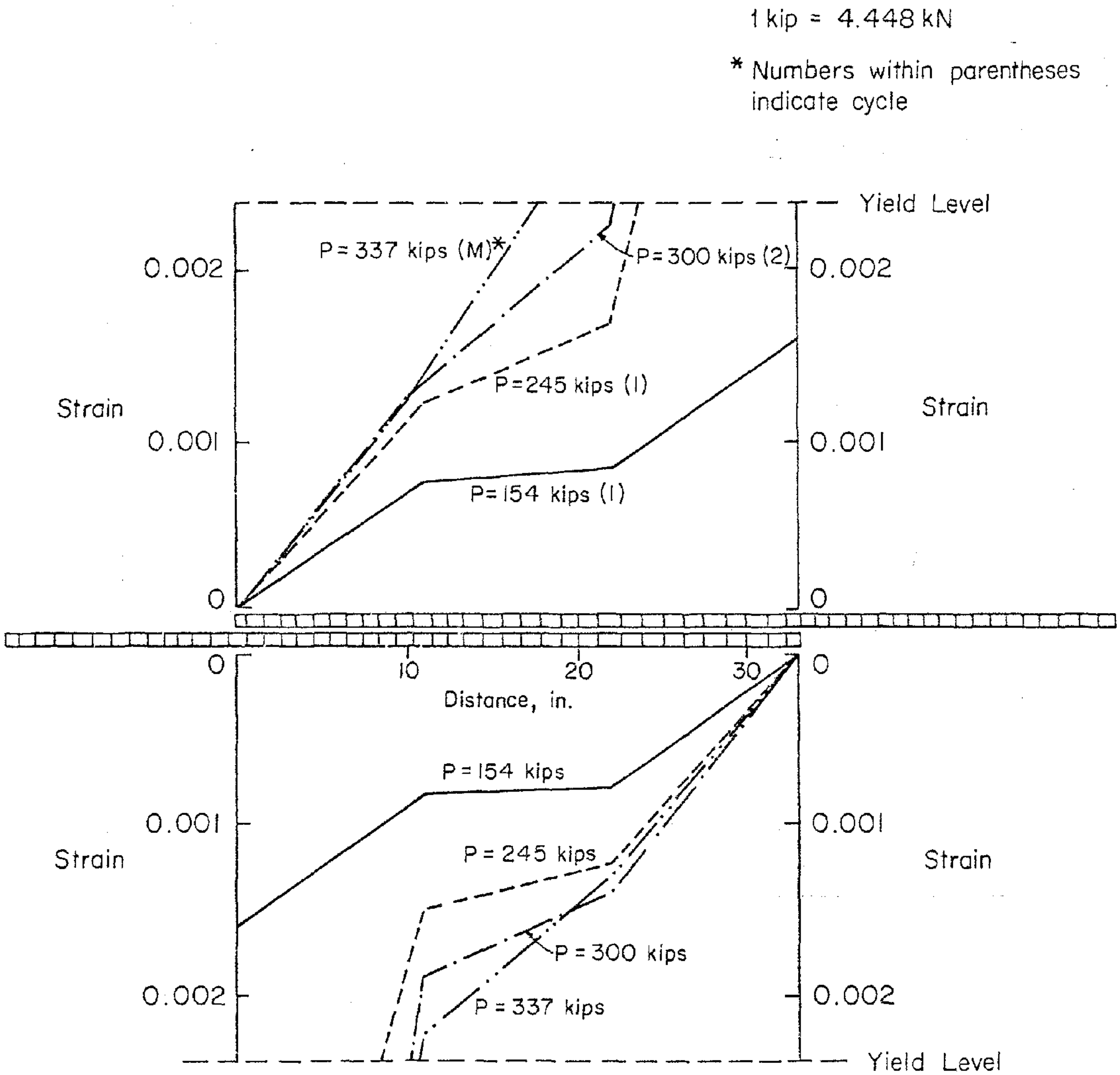


Fig. B-14 Strain Distribution Along Inner Splice of Specimen S6-2

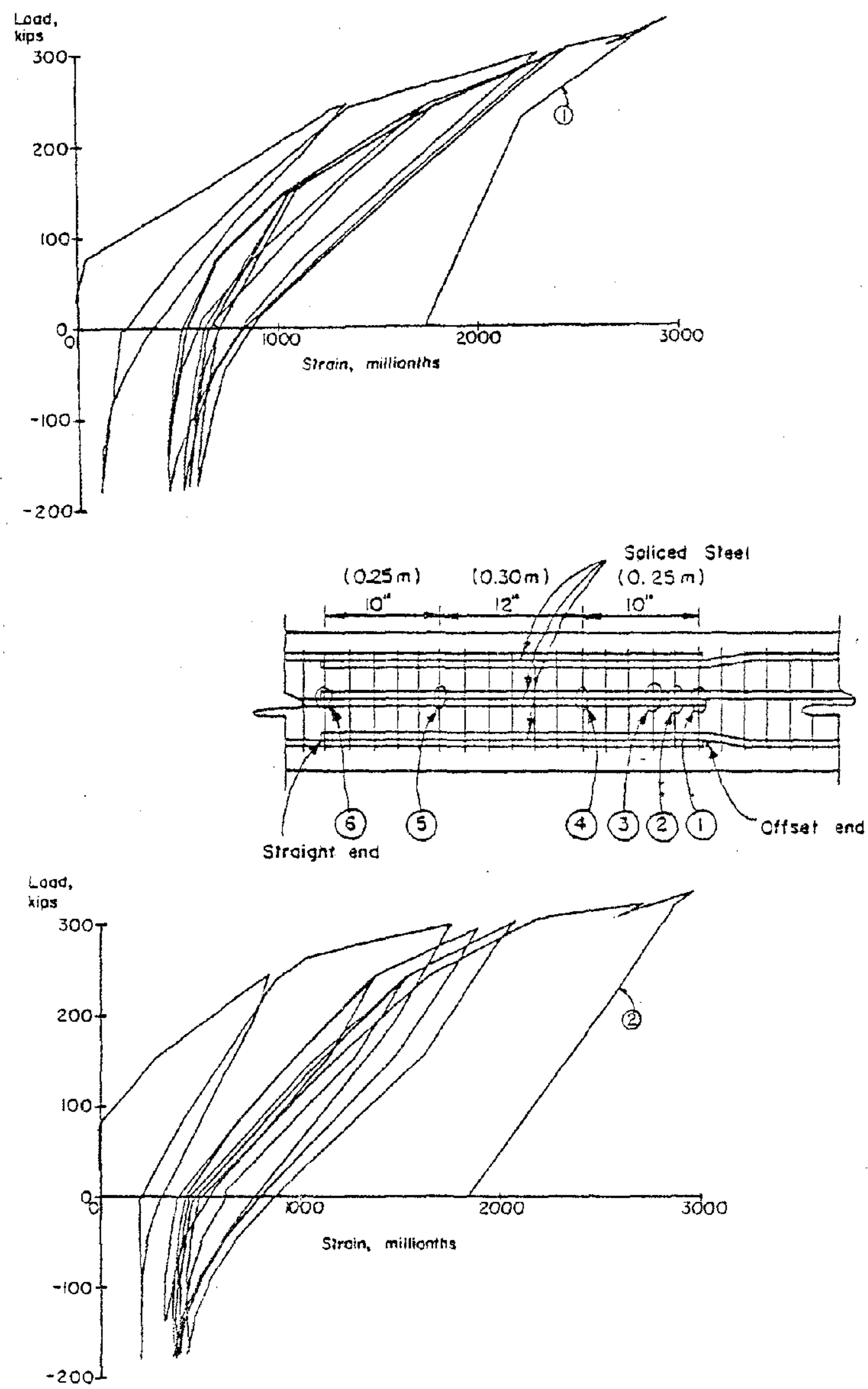


Fig. B-15 Load versus Hoop Strains for Specimen S6-2: Gages 1 and 2

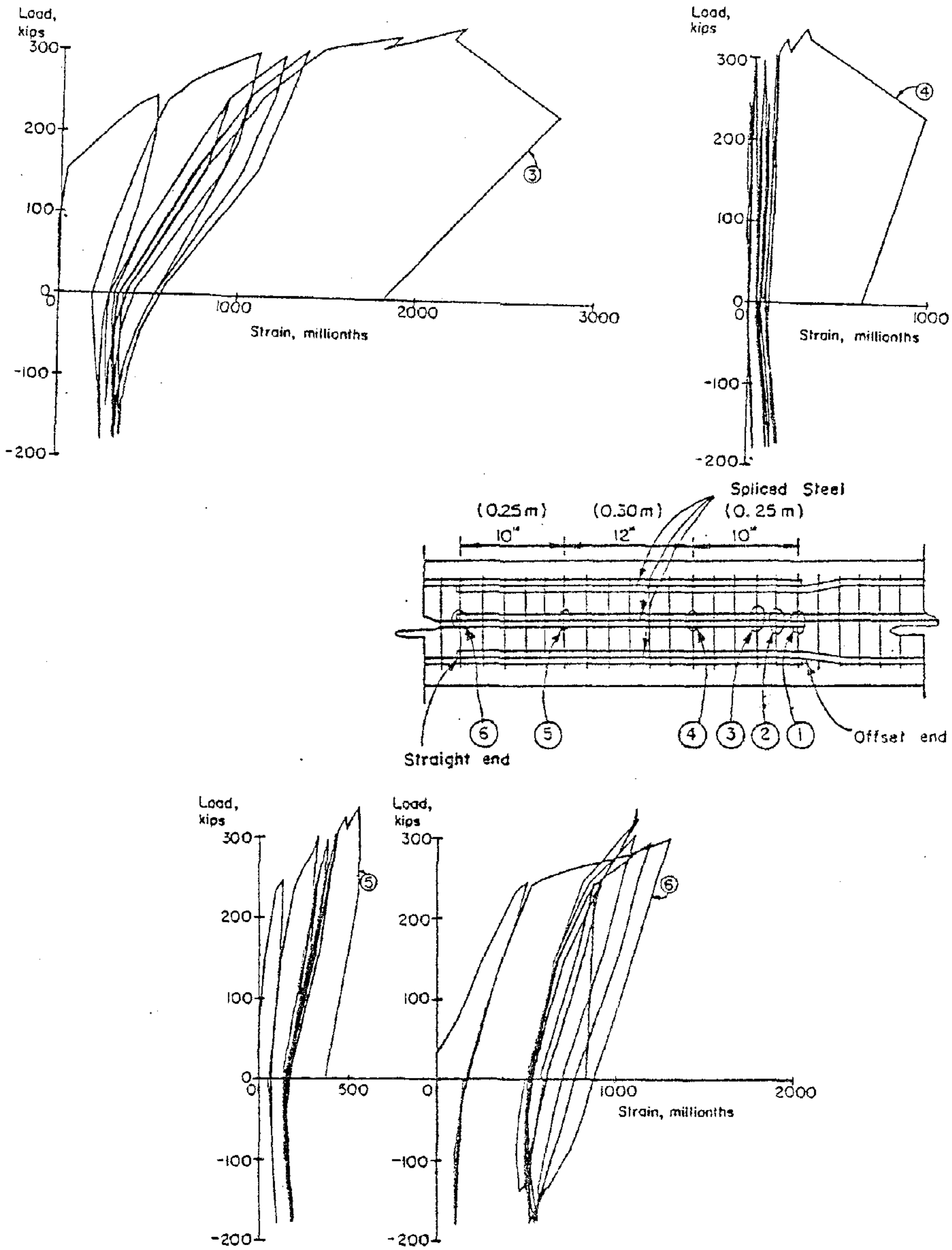


Fig. B-16 Load versus Hoop Strains for Specimen S6-2: Gages 3, 4, 5, and 6 at the offset end, and that this hoop became effective after yielding of the longitudinal reinforcement occurred. Since both ends of the splice are practically identical except for the presence of the offset and the relative position of the lapped bars, the main source of transverse expansion within the splice is the internal moment induced by the eccentricity of the lapped bars. Offsetting bars causes bursting forces at the offset-end and concentrates bursting of the concrete in a small region.

Bursting or radial forces are resisted by concrete cover, hoop reinforcement, and dowel action of the exterior corner bar. At the offset end, radial forces are resisted mainly by hoop reinforcement. The contribution of the concrete cover at the offset-end is reduced by the bursting forces induced by offsetting of bars. This explains the high concentration of damage at the offset end region of the splices.

Splitting cracks were first observed at the ends of the splice and along the interior lapped bars at a load of 232 kips (1032 kN) during first half cycle. This is also the load at which yielding of interior lapped bars was first observed.

Specimen S6-2, after being subjected to six load reversals, reached a load capacity identical to that of Specimen S6-1. However, the final mode of failure was by bar fracture. All eight bars fractured at the offset-end. Calculated yield and maximum loads are listed in Table 5.

Specimen S6-3

The main difference between Specimen S6-3 and previous specimens was the amount of transverse reinforcement. Specimen S6-3 had 50% of the hoop reinforcement that was used in Specimens S6-1 and S6-2. Specimen S6-3 was subjected to load reversals.

Plots of load versus elongation are shown in Fig. B-17. Initial and final crack patterns are shown in Fig. B-18.

Cracking of the concrete was first observed at a load of 46 kips (205 kN),. Figure B-19 shows crack widths along the splice. The magnitude and distribution of cracks were similar to those observed in Specimens S6-1 and S6-2. As in Specimen S6-2, load reversals caused progressive permanent deformations.

Figures B-20, B-21, and B-22 show strains along the spliced reinforcement. Figure B-23 shows strains along the corner bars at load stages of the first two cycles. The anti-symmetry and the tendency of the strain distribution to become linear are apparent. Yield penetration was eventually equivalent to about 2/3 of the splice length.

Strains in hoop reinforcement are shown in Figs. B-24 and B-25. The effectiveness and sequence of yielding of the hoop reinforcement were similar to those observed in Specimen S6-2. As in Specimen S6-1, hoop No. 1 was not effective. Hoops at the ends of the splice were effective, particularly those at the offset end.

Splitting cracks were first observed at the offset end of the splice and along the interior lapped bars at a tensile load of 233 kips (1036 kN) during the first cycle. These splitting

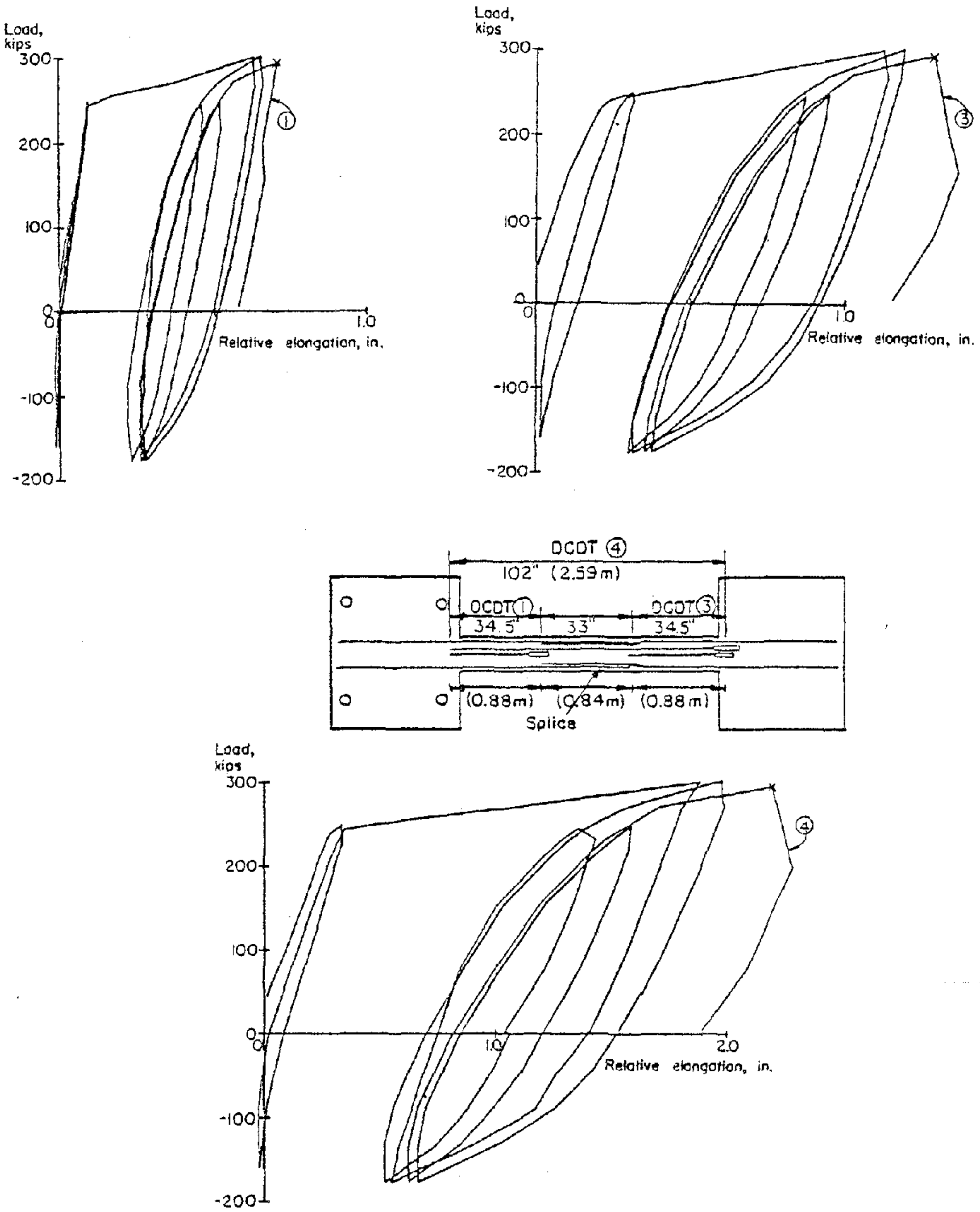
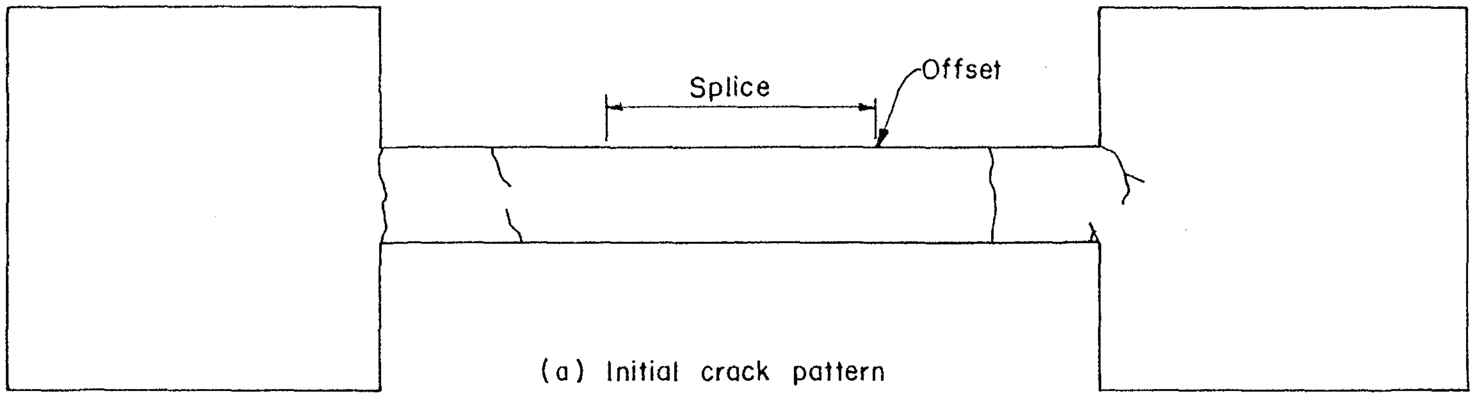
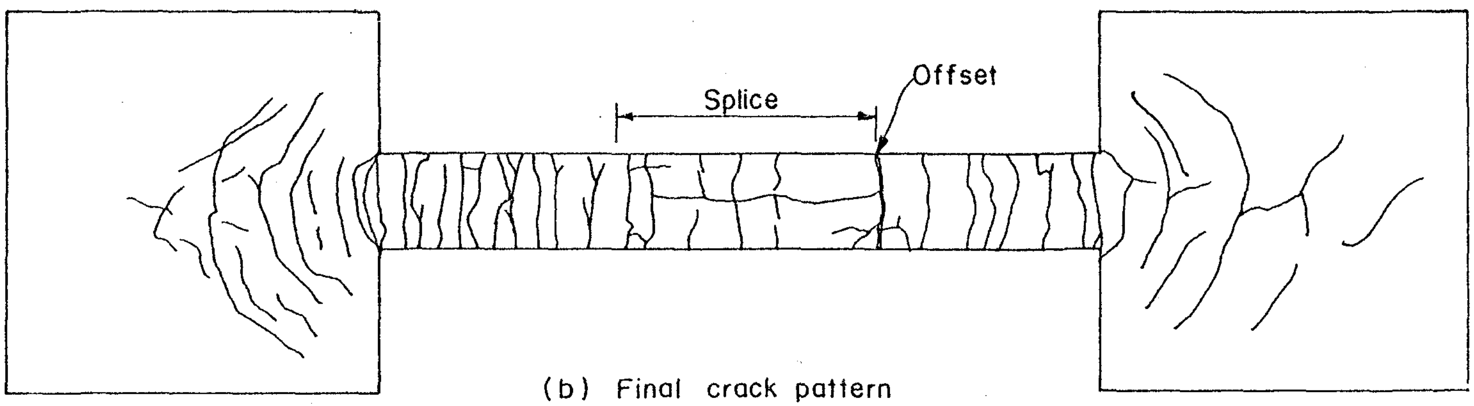


Fig. B-17 Axial Deformations of Specimen S6-3

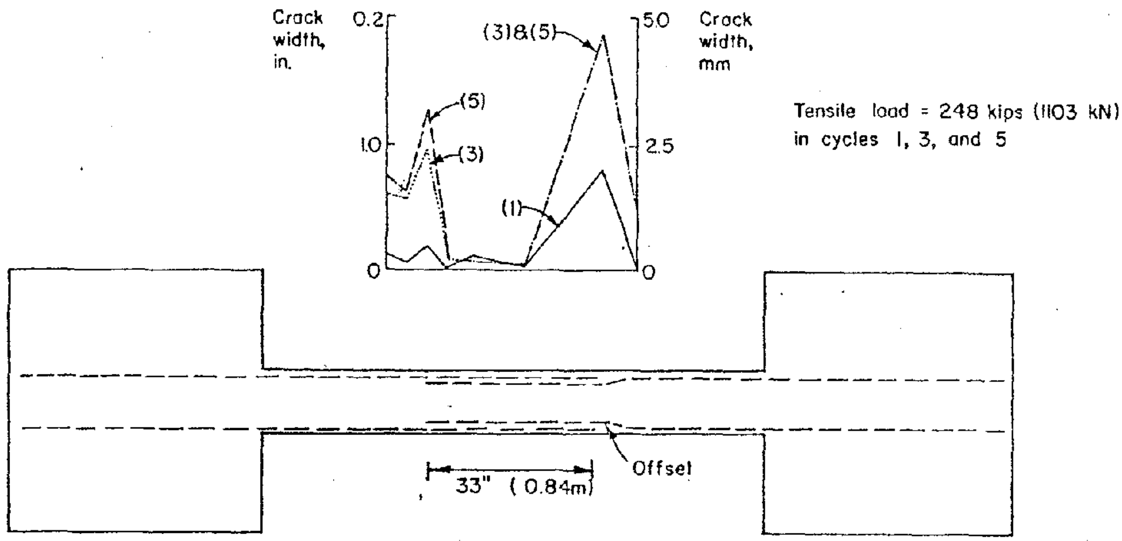


(a) Initial crack pattern

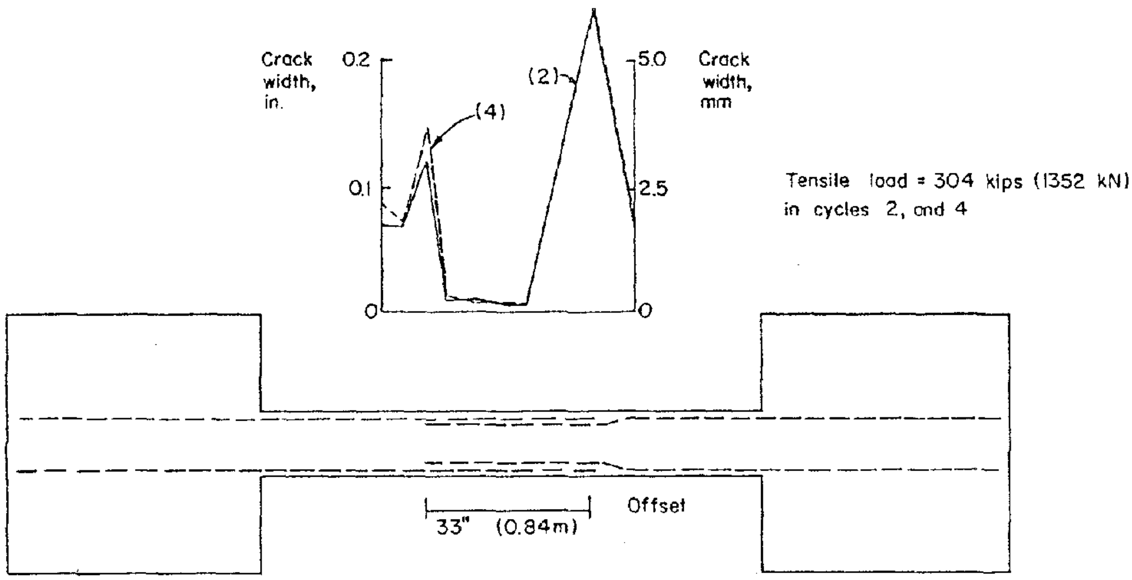


(b) Final crack pattern

Fig. B-18 Crack Patterns of Specimen S6-3



(a) Tensile load = 248 kips (1103 kN)



(b) Tensile load = 304 kips (1352 kN)

Fig. B-19 Measured Crack Widths in Specimen S6-3

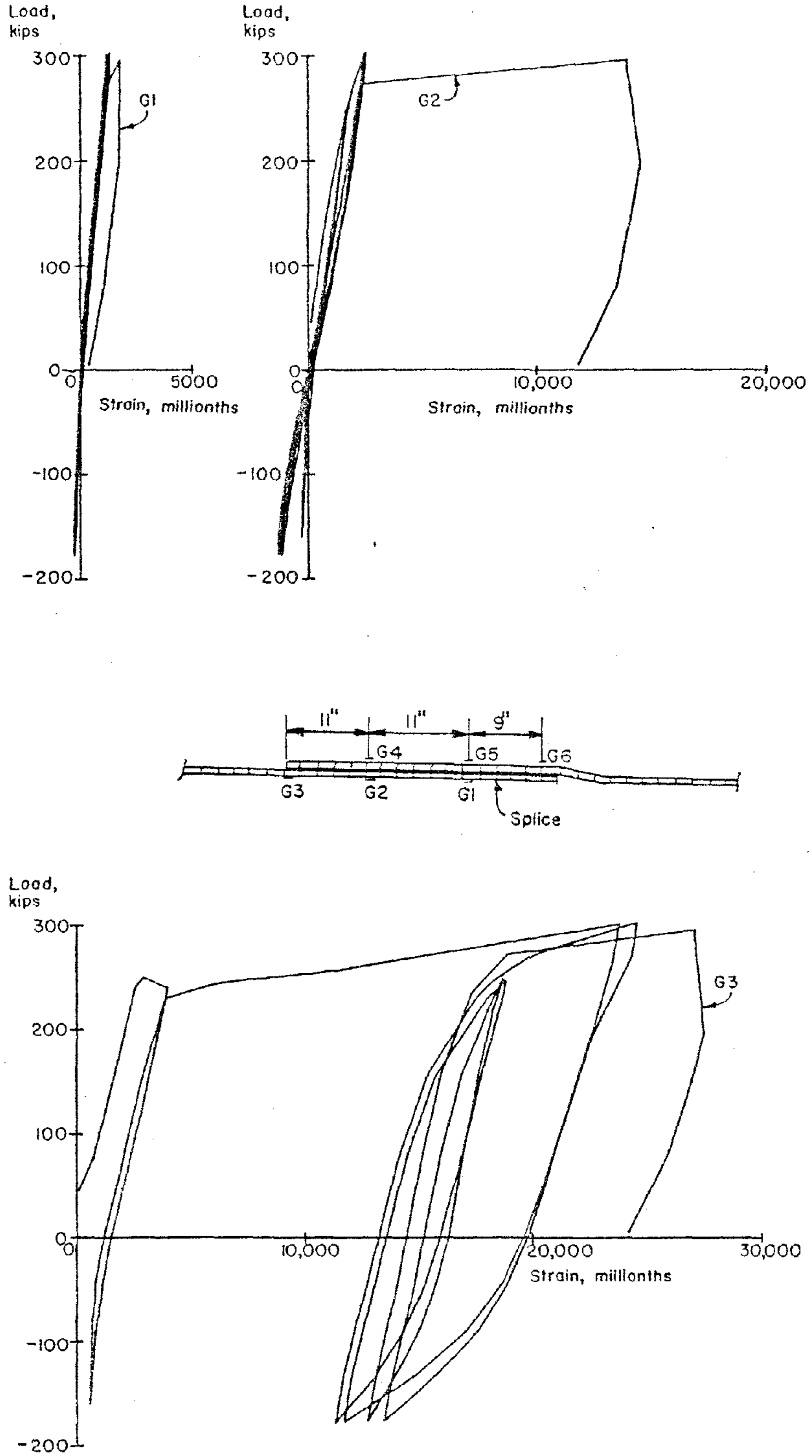


Fig. B-20 Load versus Steel Strains in Corner Bars for Specimen S6-3: Gages G1, G2, and G3

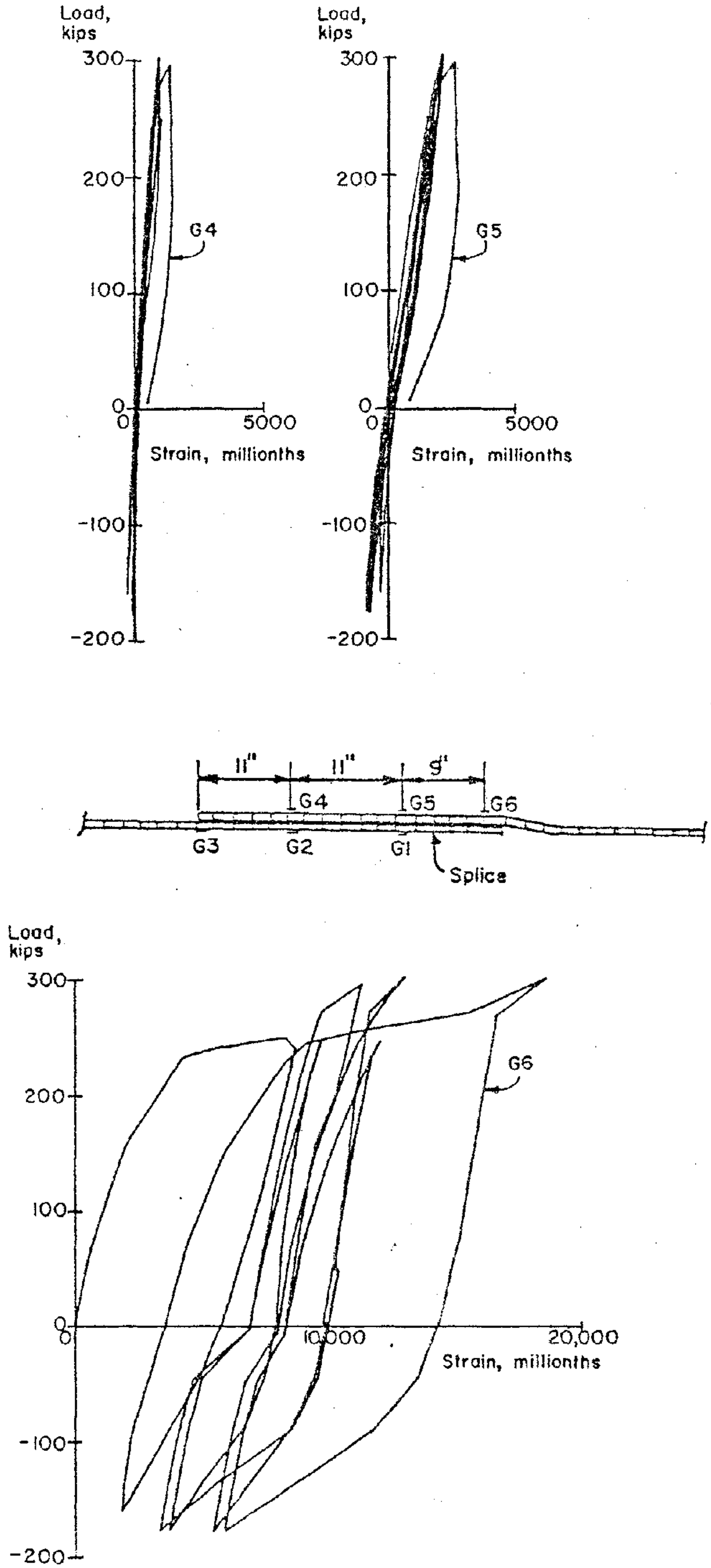


Fig. B-21 Load versus Steel Strains in Corner Bars for Specimen S6-3; Gages G4, G5, and G6

Gage G7 Damaged During Test

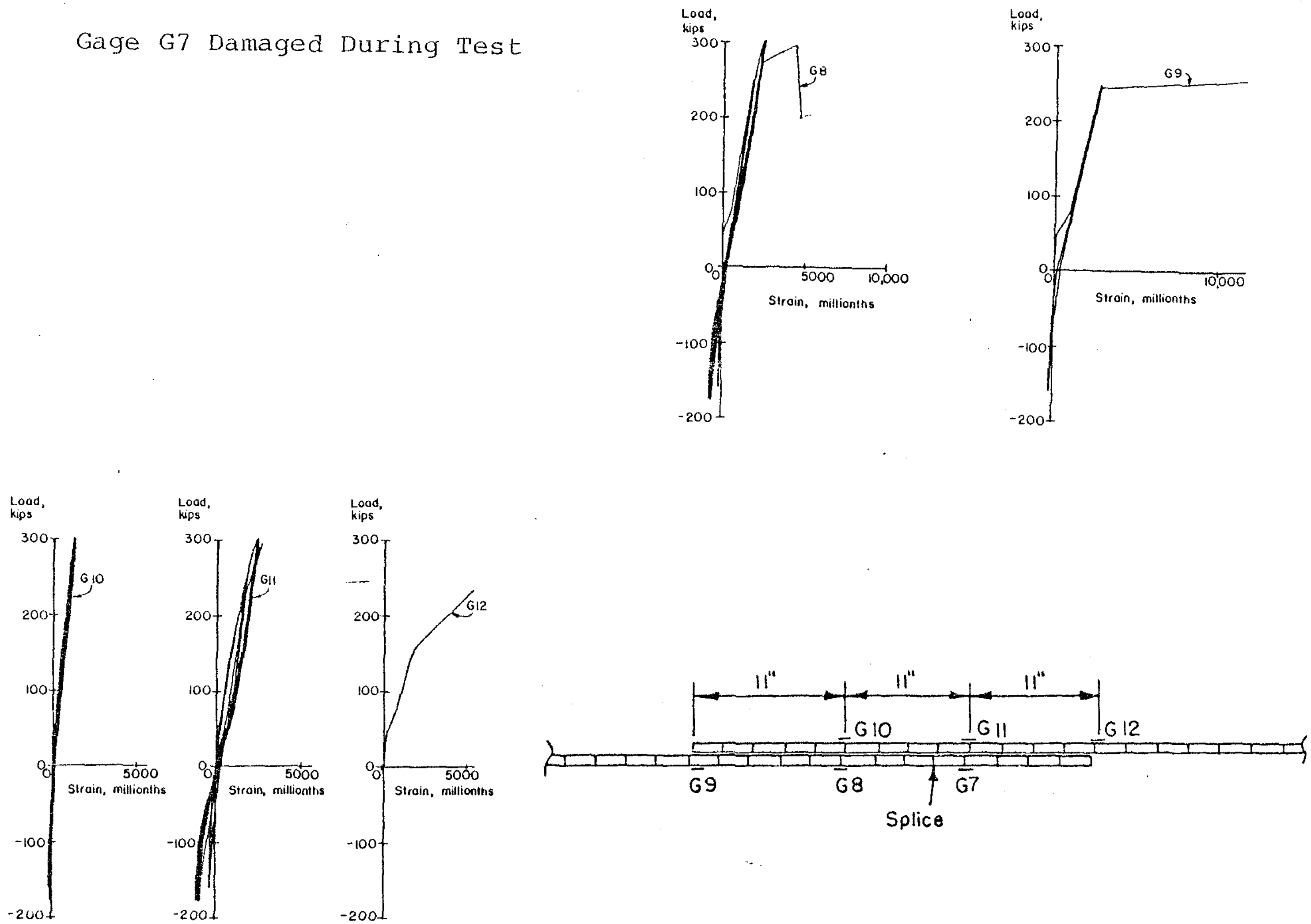


Fig. B-22 Load versus Steel Strains in Inner Bars for Specimen S6-3

1 kip = 4.448 kN

* Numbers within parentheses indicate cycle

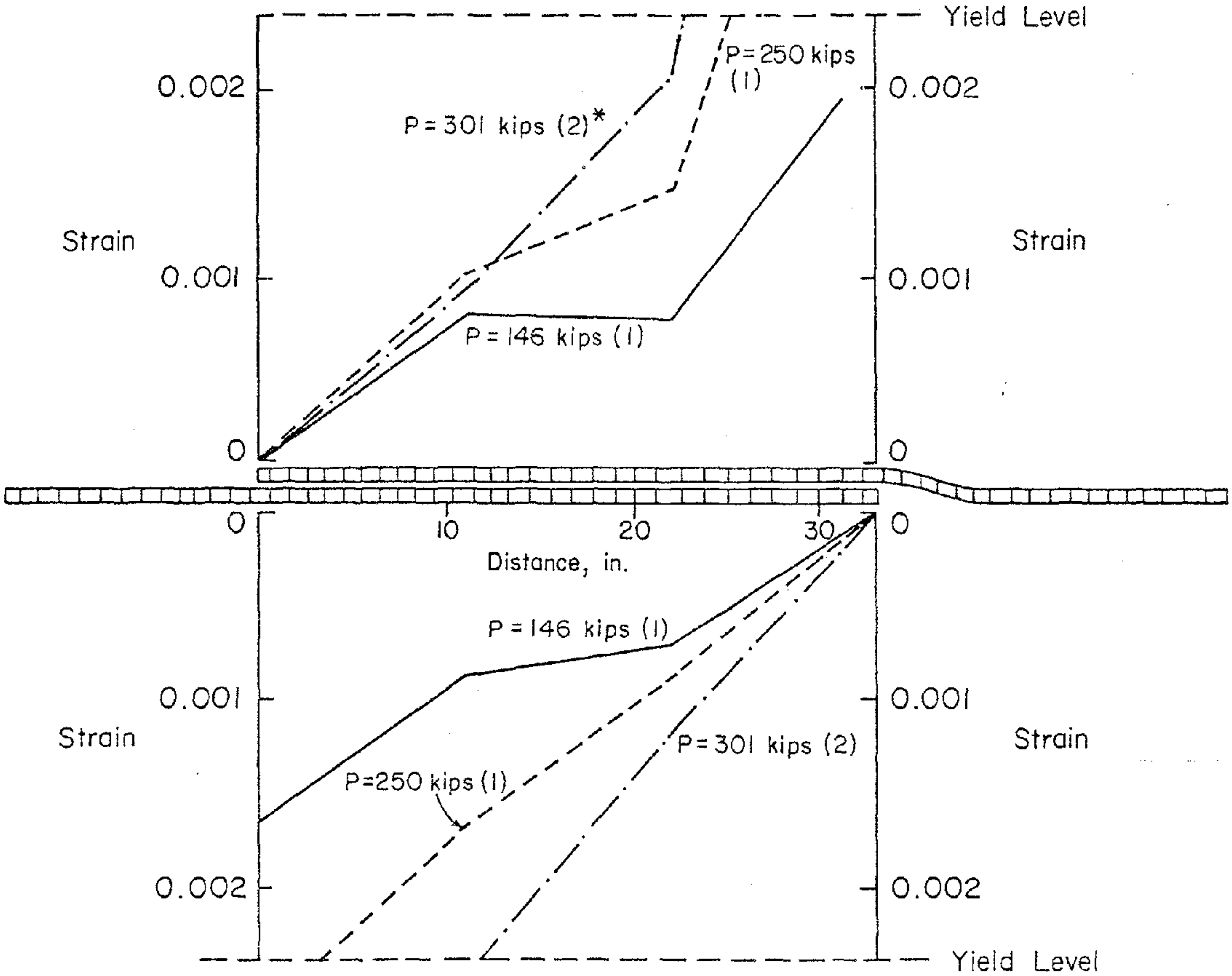


Fig. B-23 Strain Distribution Along Corner Splice of Specimen S6-3

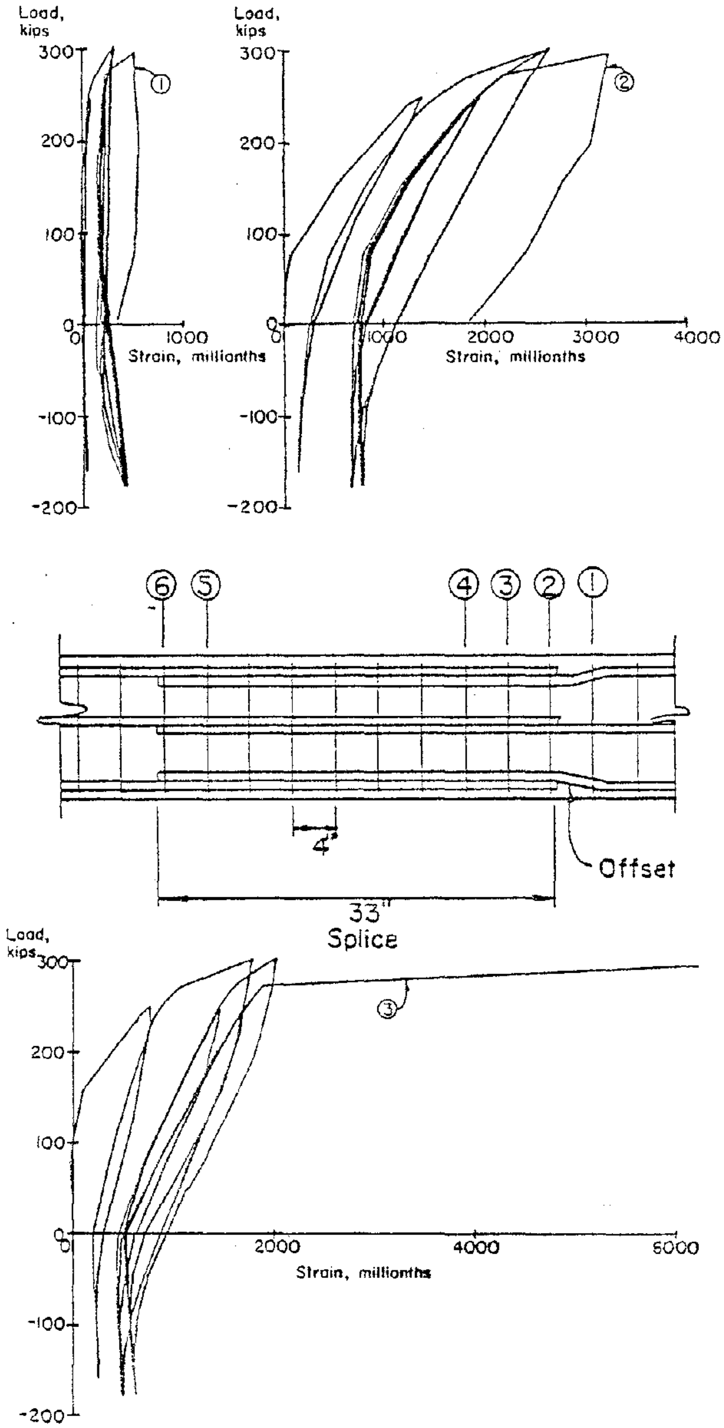


Fig. B-24 Load versus Hoop Strains for Specimen S6-3: Gages 1, 2, and 3

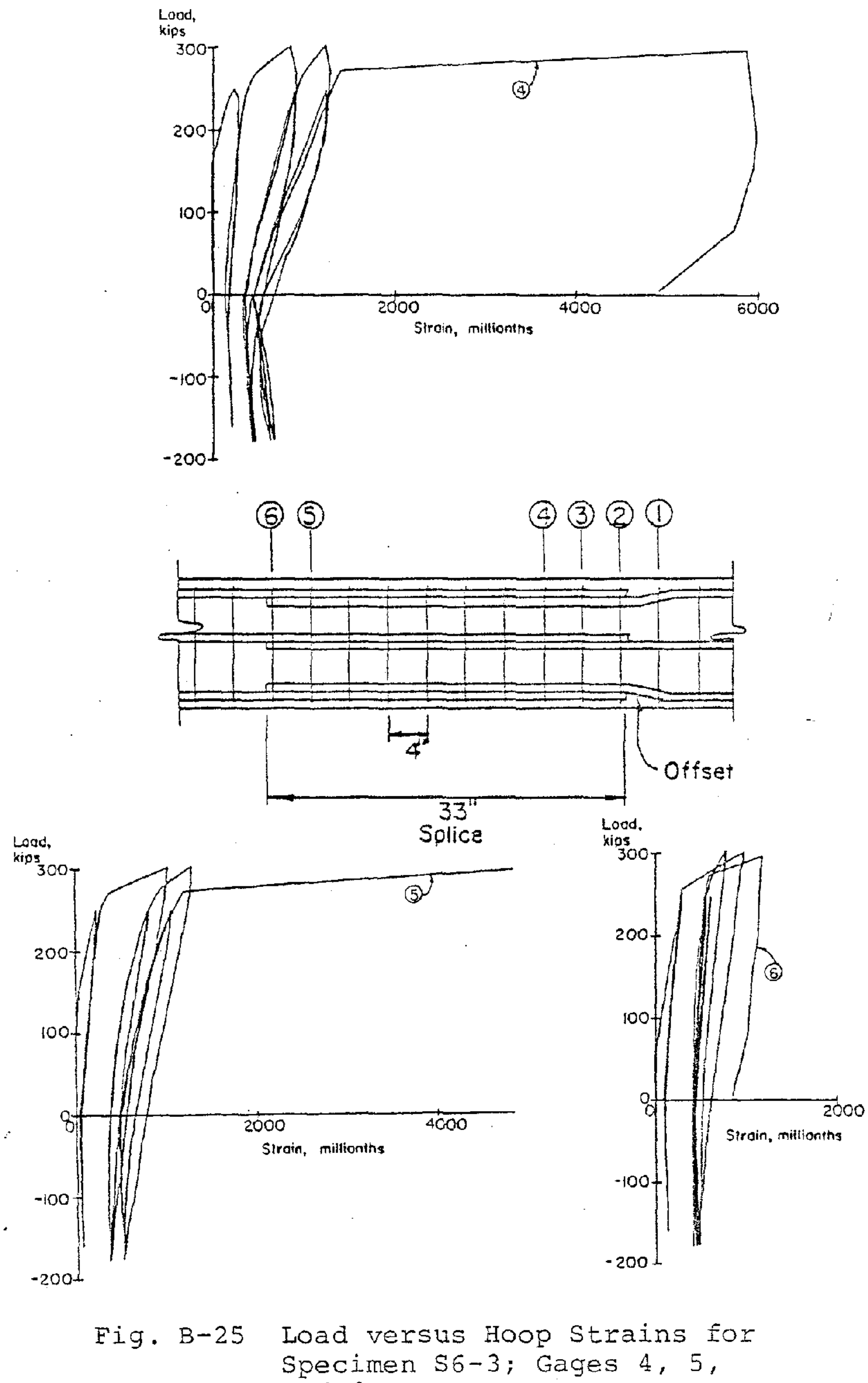


Fig. B-25 Load versus Hoop Strains for Specimen S6-3; Gages 4, 5, and 6 cracks penetrated 8 in. (0.20 m) into the splice at the peak tensile load of the second cycle. At the peak tensile load of the sixth cycle, splitting cracks crossed most of the splice causing the inner bars to pull out. Splitting cracks were also observed along the corner bars as shown in Fig. B-18. The corner splitting cracks were first observed at the peak tensile load of the third cycle. It is important to note that immediately before the inner bars pulled out, hoop Nos. 3, 4, and 5 yielded. This may have permitted propagation of splitting cracks along the splice.

Specimen S6-3 failed at the peak tensile load of the sixth cycle. The mode of failure was by "splitting-bond" of the inner bars. Corner bars fractured after inner bars pulled out. Calculated and measured strengths are listed in Table 5.

Specimen S6-4

Specimen S6-4 was a companion to Specimen S6-3, but Specimen S6-4 was monotonically loaded. Strength, ductility, and behavior of S6-4 were similar to those of S6-3.

Plots of load versus elongation are shown in Fig. B-26. Initial and final crack patterns are shown in Fig. B-27.

Figure B-28 shows crack widths along the splice. Most of the axial deformation was concentrated at the offset end.

Figures B-29, B-30, and B-31 show strains along the spliced reinforcement. Figure B-31 shows the anti-symmetry and the tendency of the strain distribution to become linear. The data indicate a yield penetration of about 2/3 of the splice length.

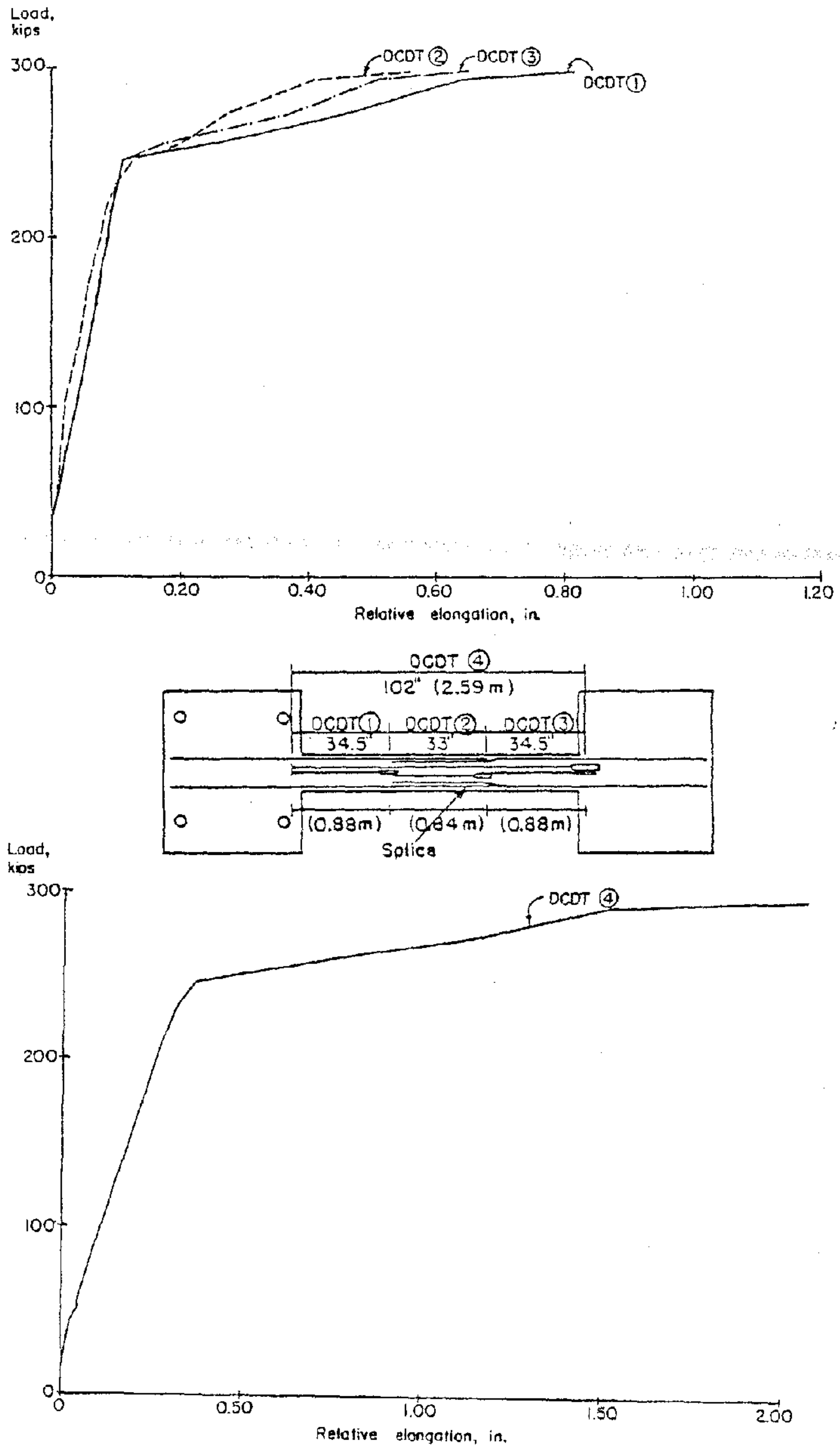
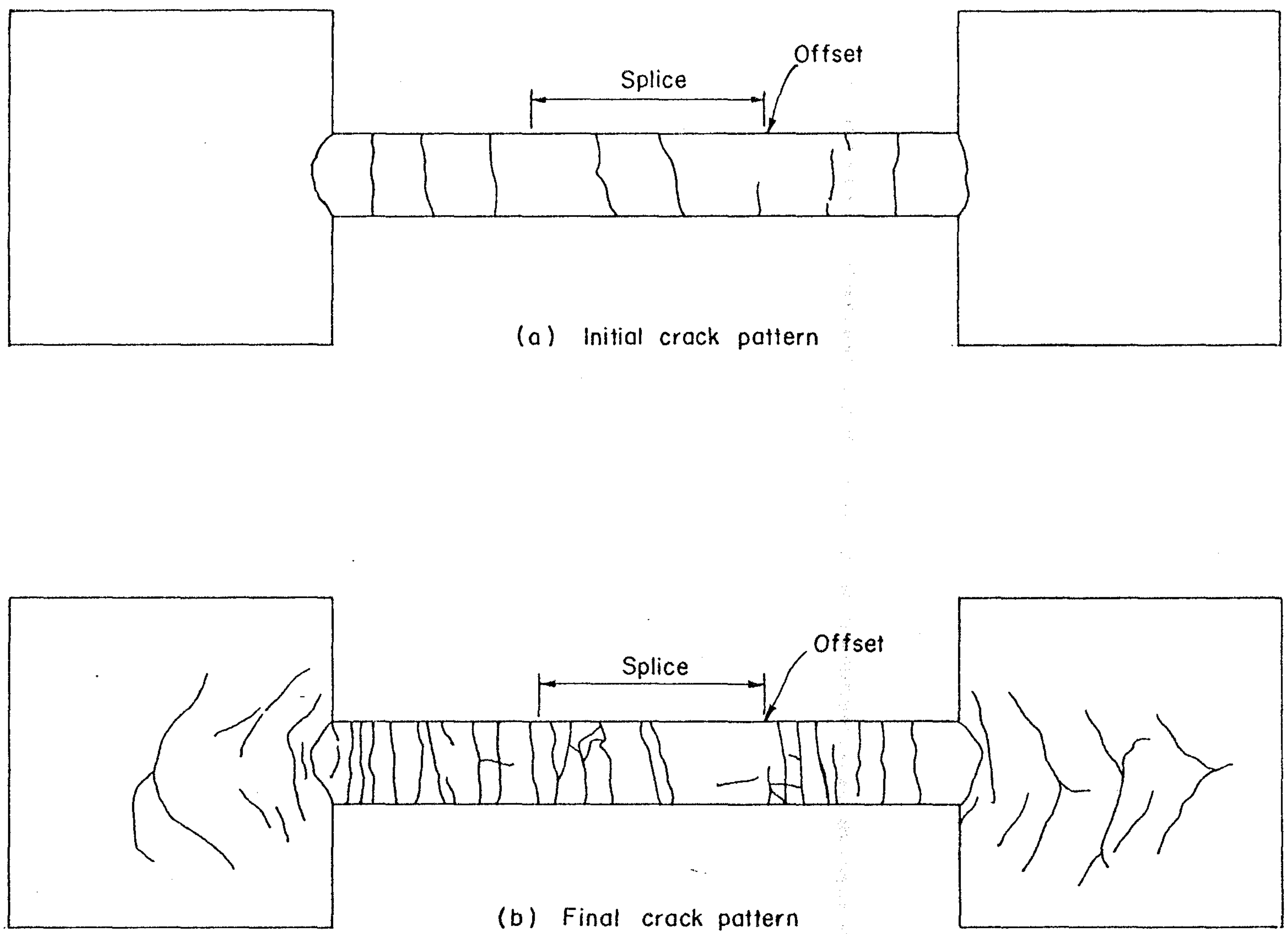


Fig. B-26 Axial Deformations of Specimen S6-4



(a) Initial crack pattern

(b) Final crack pattern

Fig. B-27 Crack Patterns of Specimen S6-4

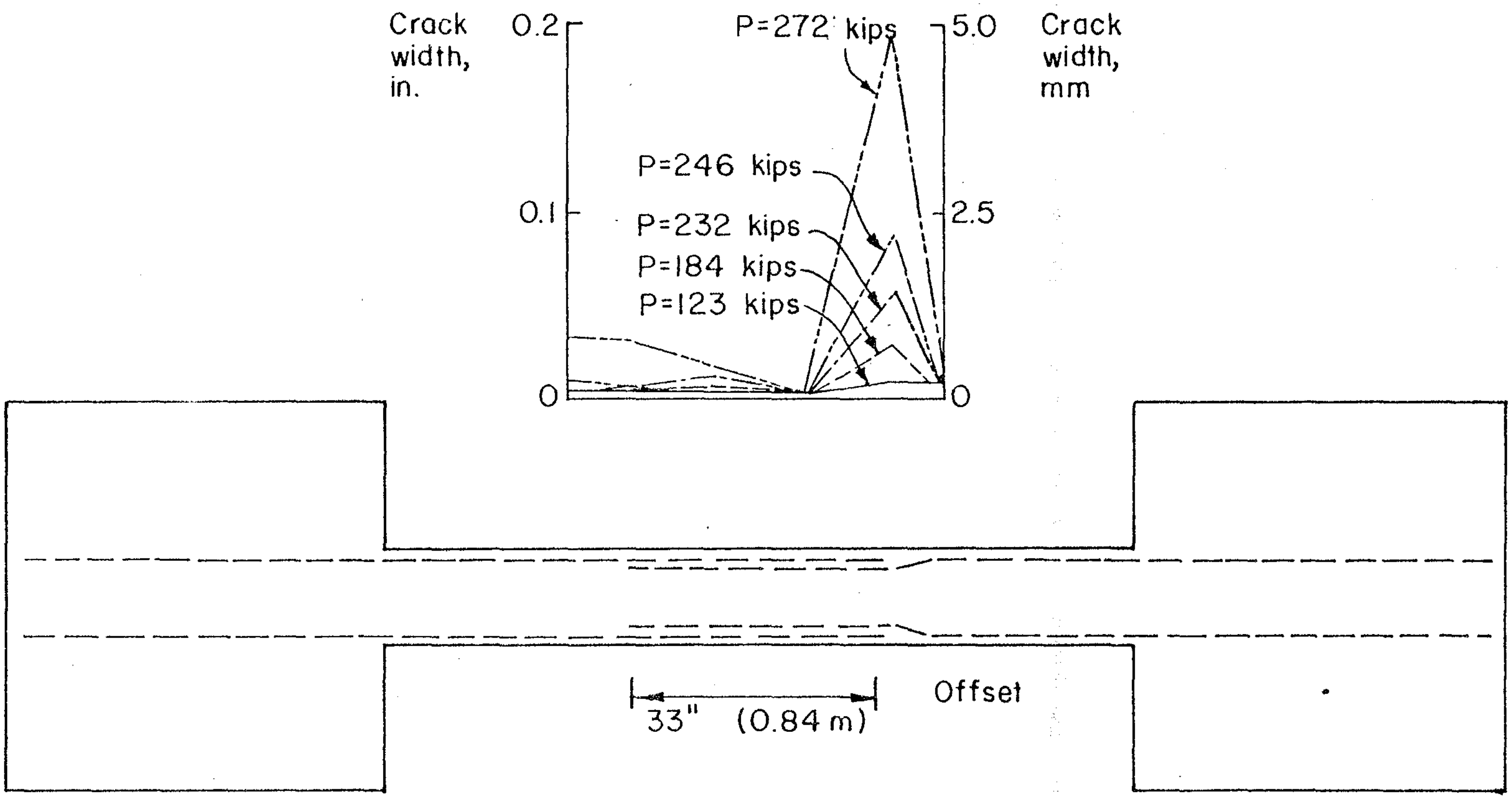
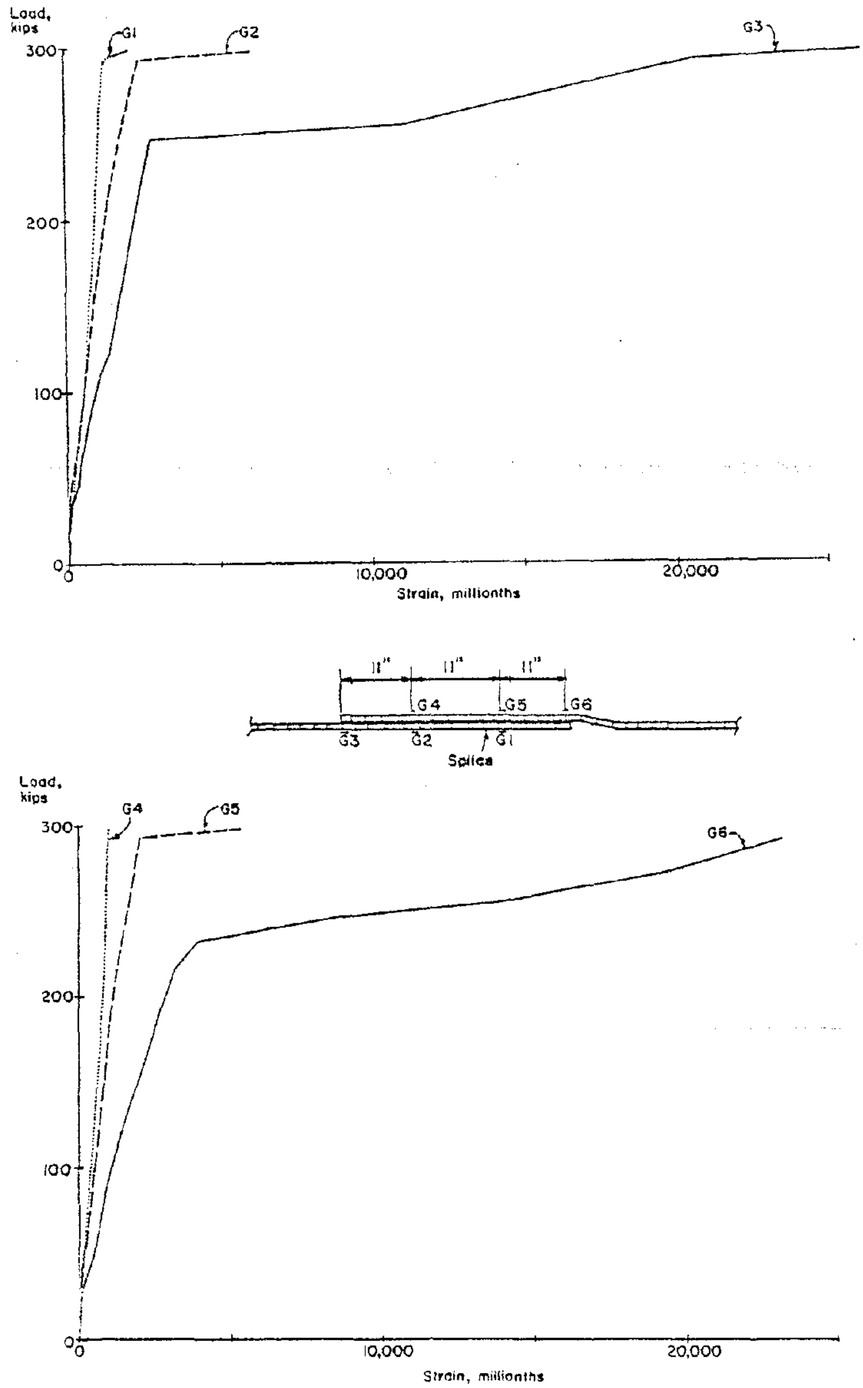


Fig. B-28 Measured Crack Widths in Specimen S6-4



B-29 Load versus Steel Strains in Corner Bars for Specimen S6-4

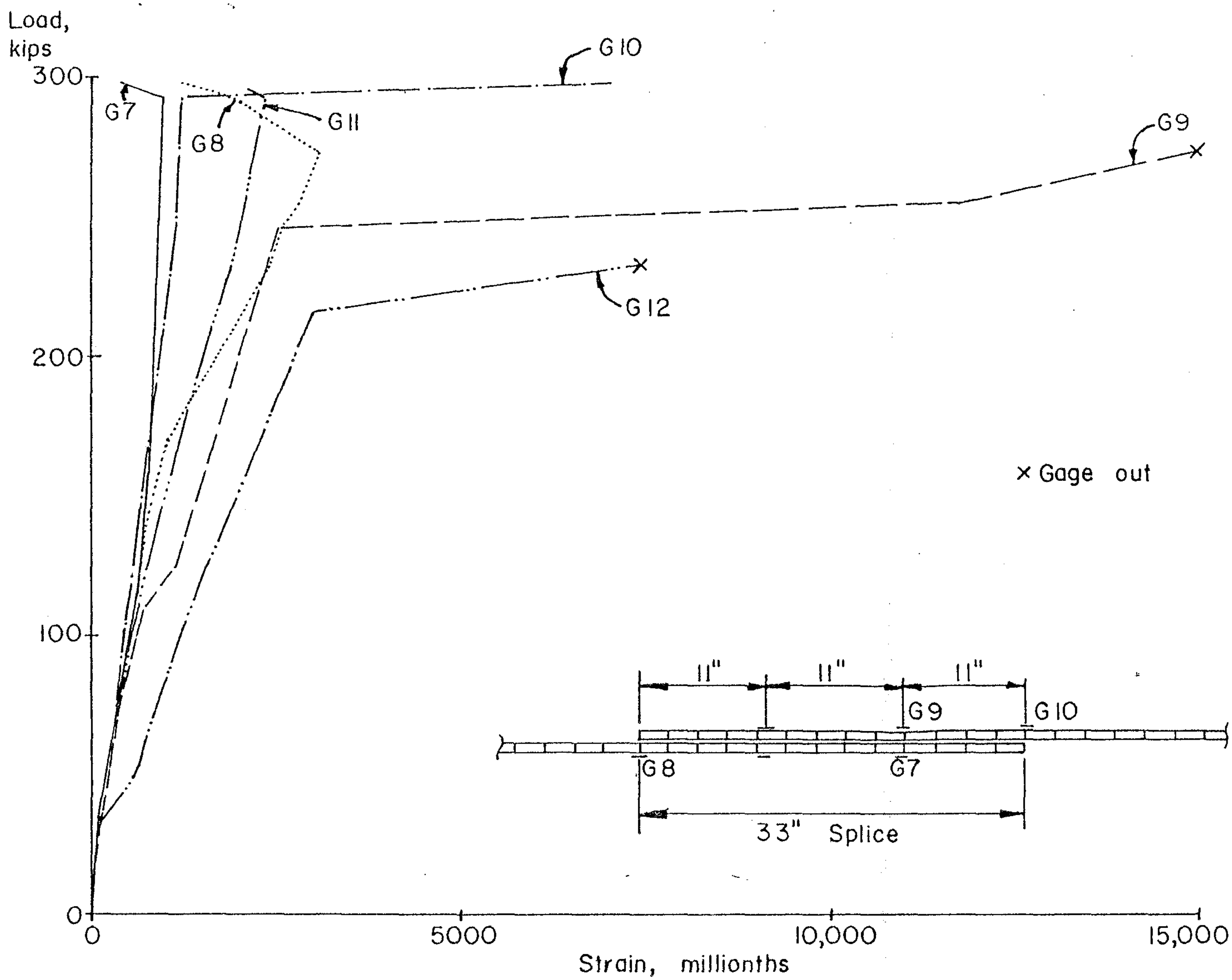


Fig. B-30 Strain Distribution Along Inner Bars for Specimen S6-4

1 kip = 4.448 kN

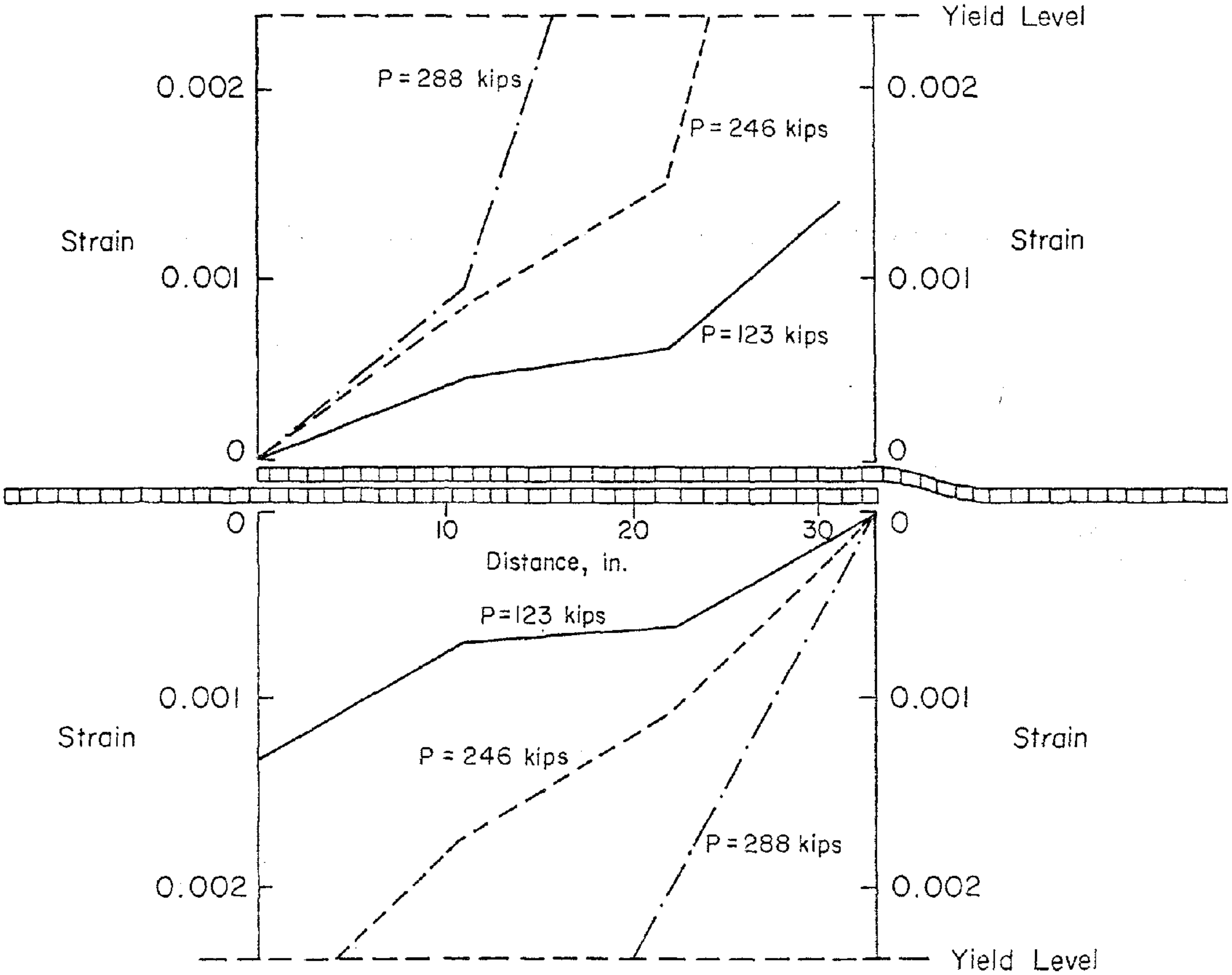


Fig. B-31 Strain Distribution Along Corner Splice of Specimen S6-4

Strains in hoop reinforcement are shown in Fig. B-32. The effectiveness and sequence of yielding of the hoop reinforcement were similar to those observed in Specimen S6-3. As in previous specimens, hoop No. 1 was ineffective.

Splitting cracks were first observed at the offset end along the corner and interior lapped bars at a load of 184 kips (818 kN). The splitting propagated along corner bars and inner bars causing the bars to pull out at the offset. As in Specimen S6-3, hoop Nos. 3, 4, and 5 yielded immediately prior to bar pullout.

Specimen S6-4 failed by "splitting-bond" of lapped bars. Calculated and measured strengths are listed in Table 5.

S-8 Specimens

Four Specimens, S8-1, S8-2, S8-3, and S8-4, were built and tested. Variables included type of loading and amount of lateral reinforcement. Specimen S8-1 was a companion monotonic loading test to Specimen S8-2.

Transverse reinforcement in Specimens S8-1 and S8-2 consisted of No. 3 confinement hoops spaced 2 in. (51 mm) on centers. This amount of confinement met seismic provisions of the 1976 Uniform Building Code.(2) To investigate effects of transverse reinforcement, Specimens S8-3 and S8-4 had No. 3 hoops spaced 12 in. (305 mm) and 4 in. (102 mm), respectively.

Specimen S8-3 was subjected to monotonic loading and Specimen S8-4 to reversing loading.

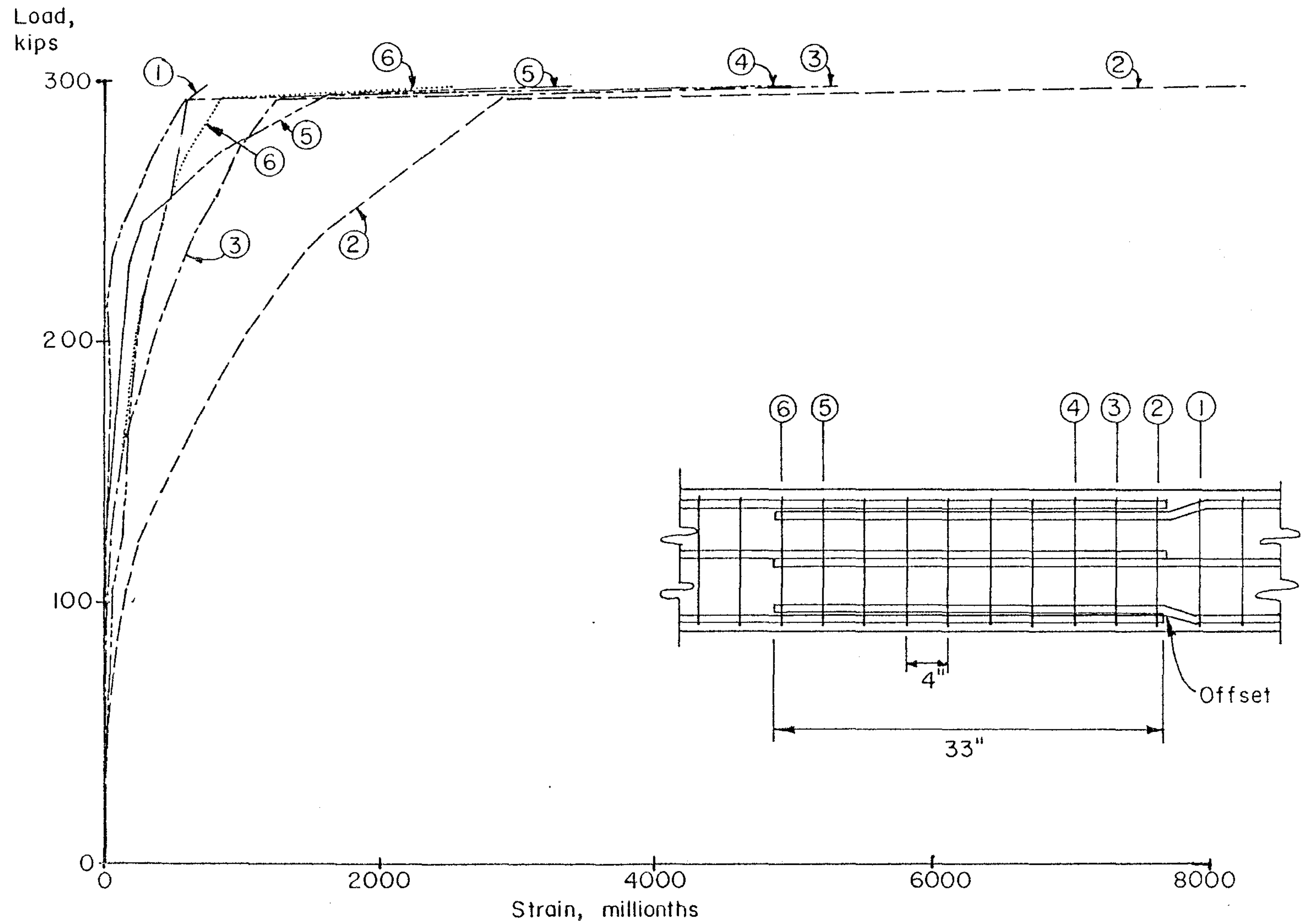


Fig. B-32 Load versus Hoop Strains for Specimen S6-4

Details of S8 Specimens are given in Figs. 4a and Table 2. The splice length was 60 in. (1.52 m). Material properties are summarized in Tables 3 and 4. Calculated and observed yield, and maximum loads and modes of failure, are summarized in Table 5.

Specimen S8-1

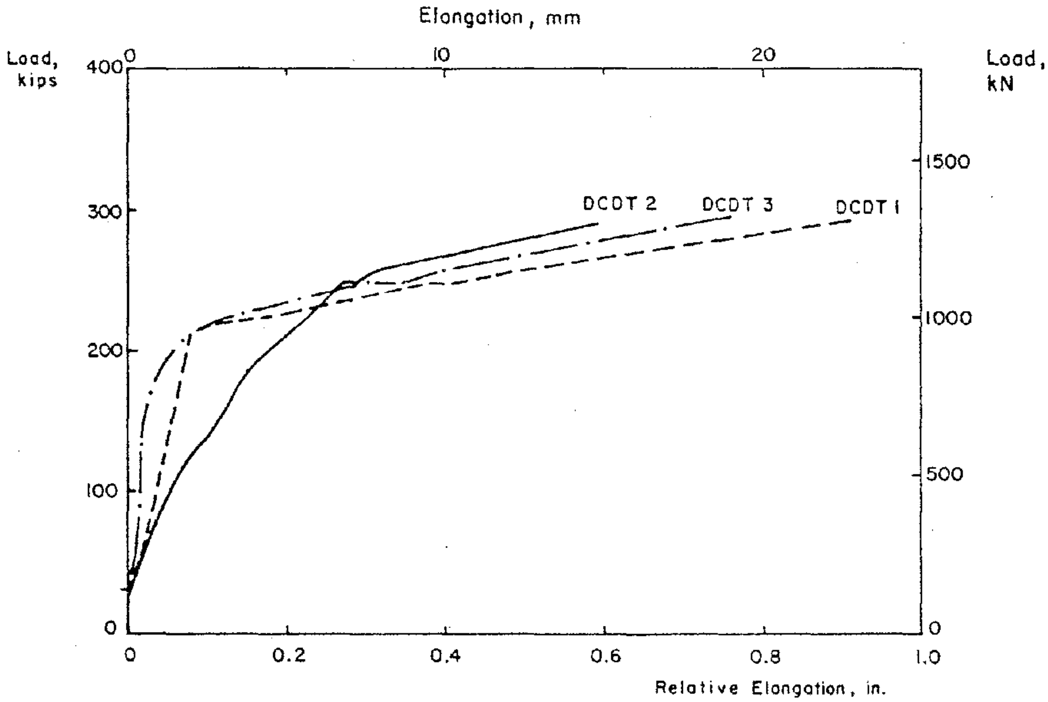
Load versus total and relative elongations are plotted in Fig. B-33. Initial and final crack patterns are shown in Fig. B-34.

Cracking was first observed at a load of 44 kips (196 kN). Initial cracks were located outside the splice length as shown in Fig. B-34(a). Under increasing load, cracks at the offset end grew much wider than those at other locations, as can be seen in Figs. B-34(b) and B-35.

Initial yielding occurred at a load of 200 kips (890 kN). This was followed by full yielding at 216 kips (961 kN). Measured longitudinal strains are plotted as a function of applied load in Fig. B-36. The distribution of longitudinal bar strains along the splice is shown in Fig. B-37. Similar to S6 Specimens, the strain distribution became linear as loads increased.

At a load of approximately 120 kips (534 kN), severe cracking of concrete cover was observed at the location of the offset. This cracking was associated with bursting stresses caused by the offset. As loading progressed the cover at the offset spalled.

Figure B-38 contains load versus strain curves for the hoop reinforcement. It is evident from the measured strains that



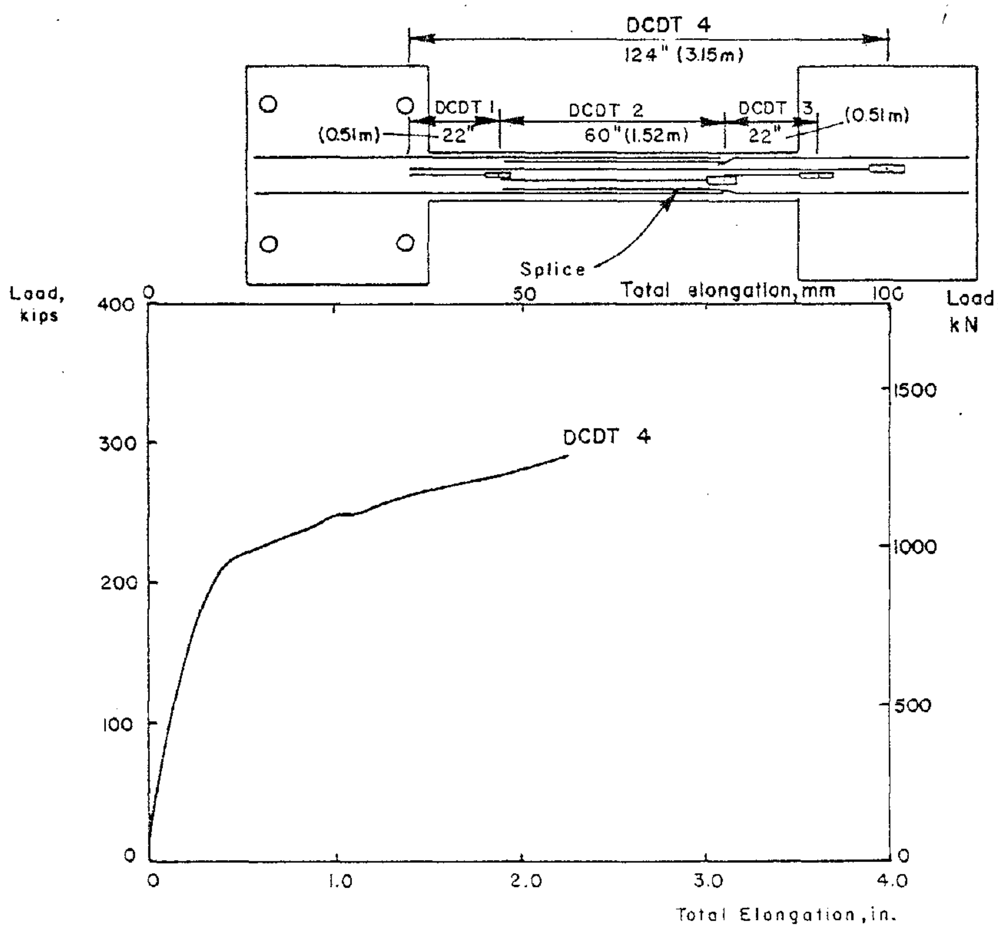


Fig. B-33 Axial Deformation of Specimen S8-1

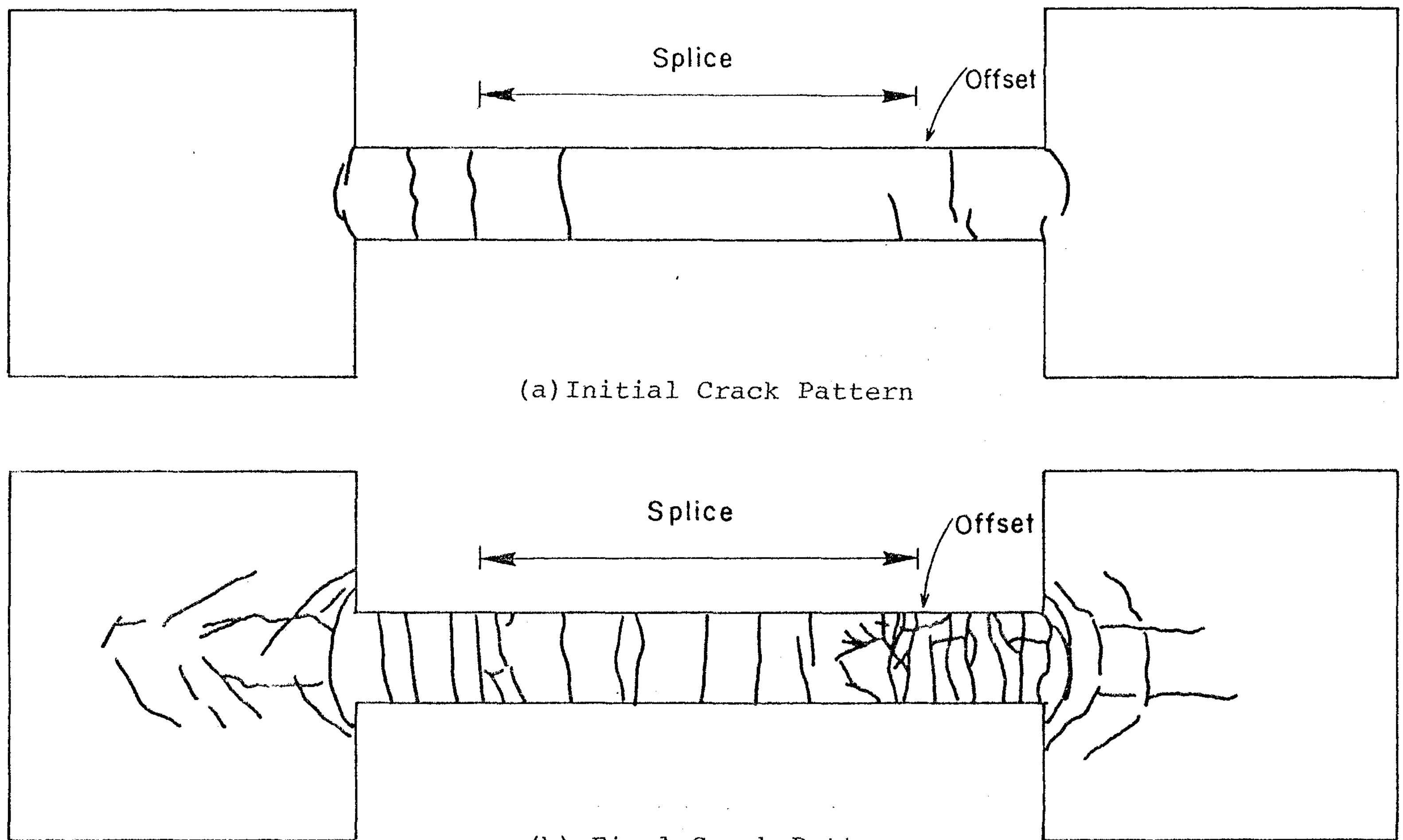


Fig. B-34 Crack Patterns of Specimen S8-1

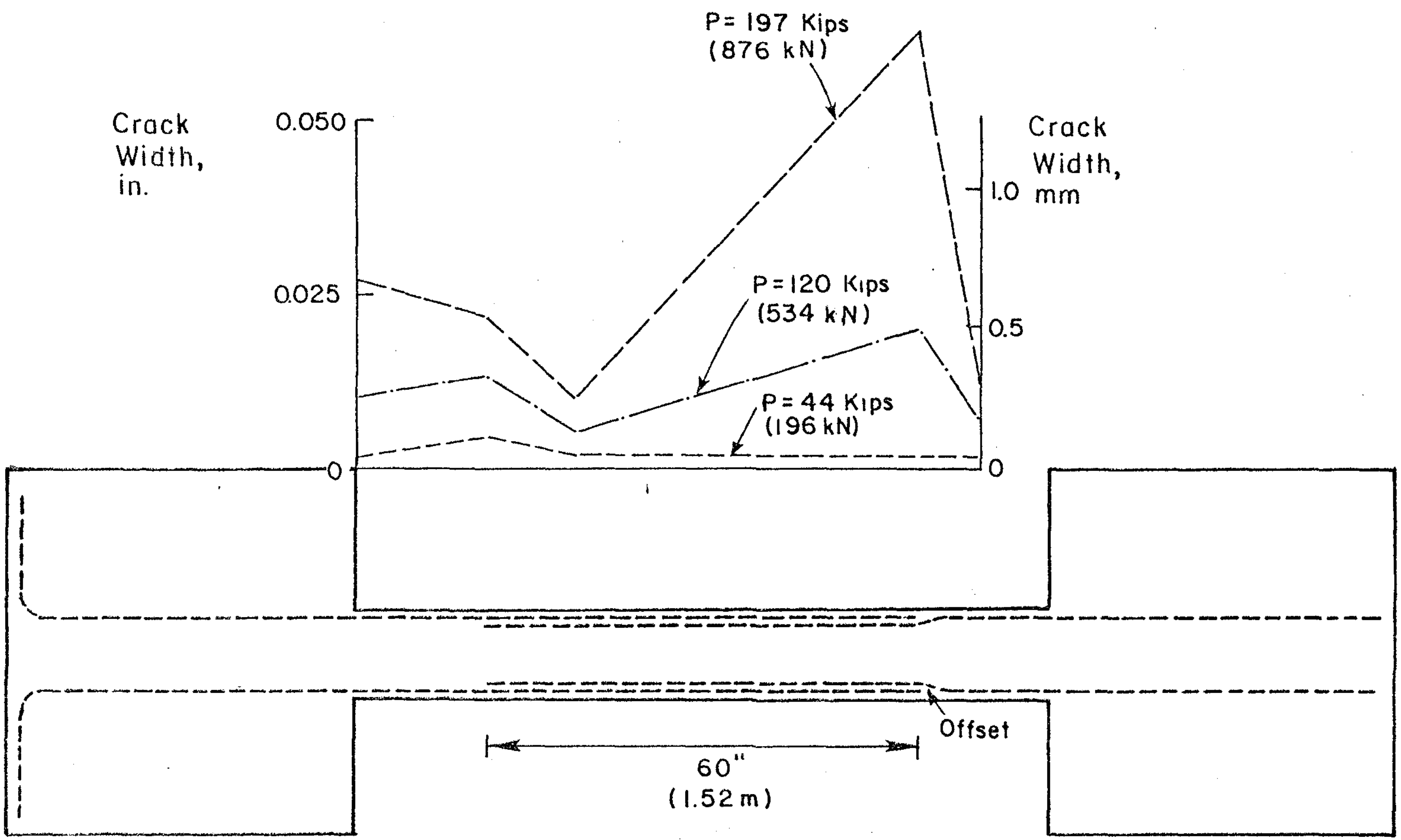


Fig. B-35 Measured Crack Widths in Specimen S8-1

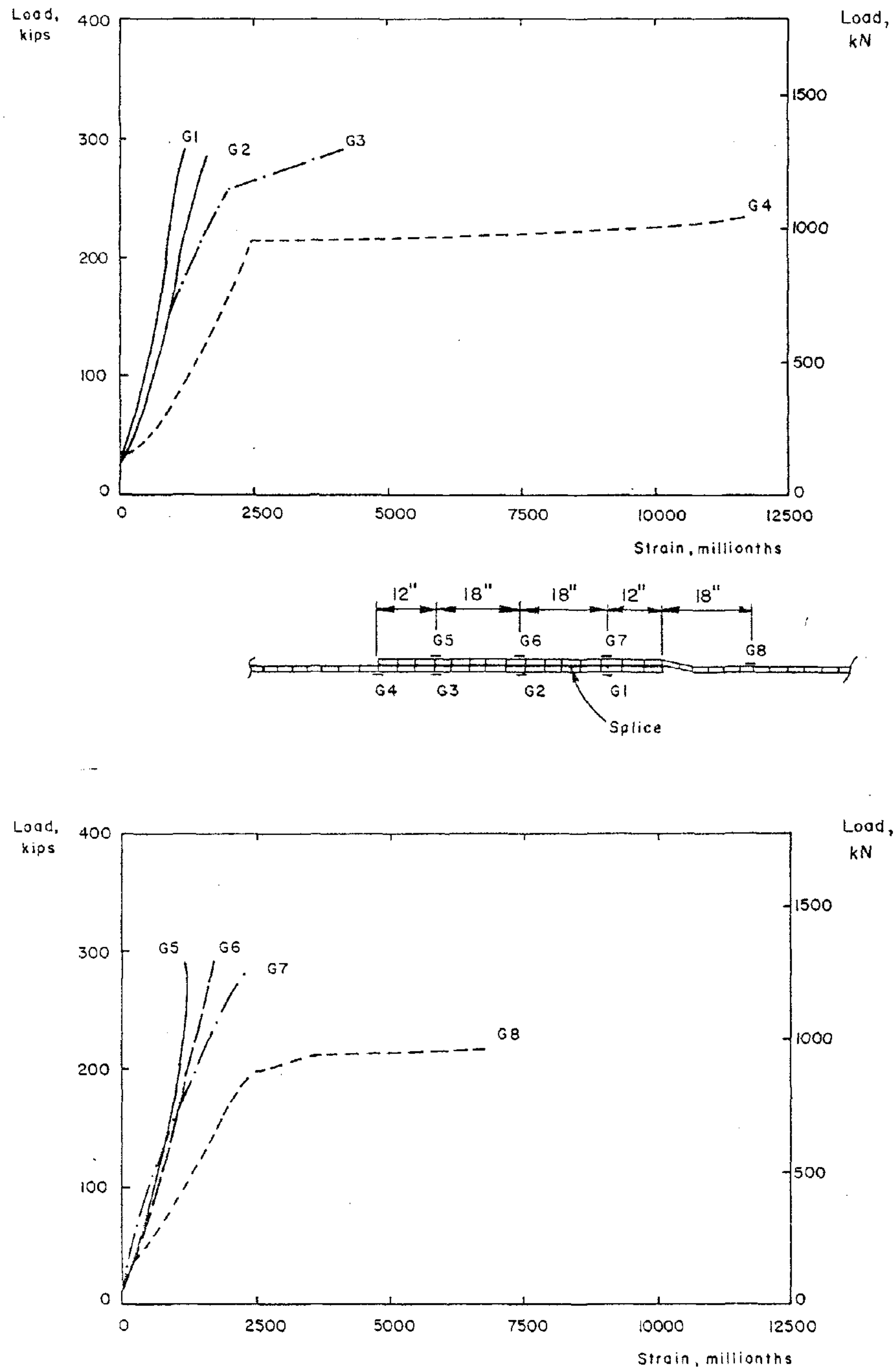


Fig. B-36 Load versus Steel Strains for Specimen S8-1

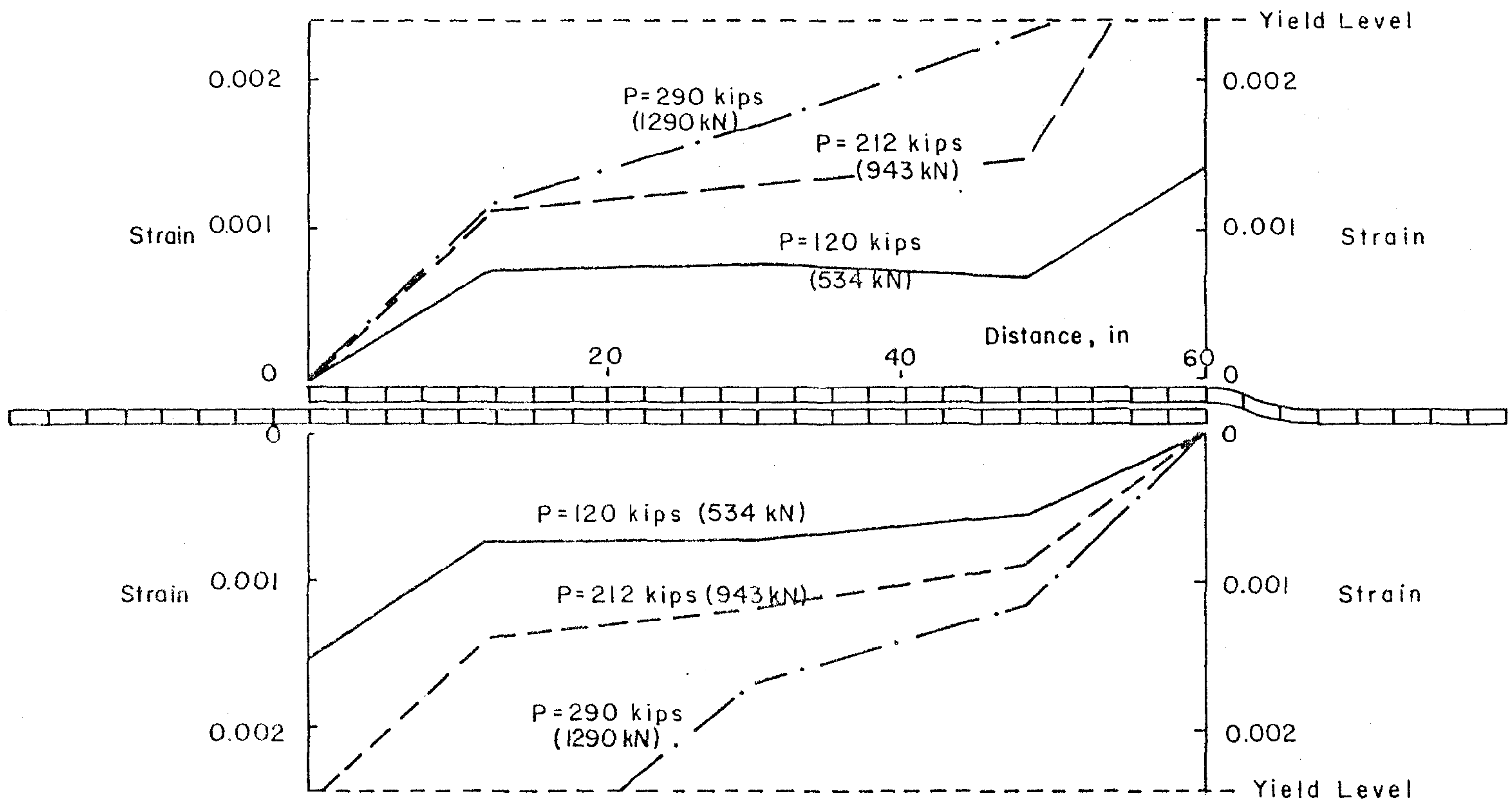


Fig. B-37 Strain Distribution Along Splice of Specimen S8-1

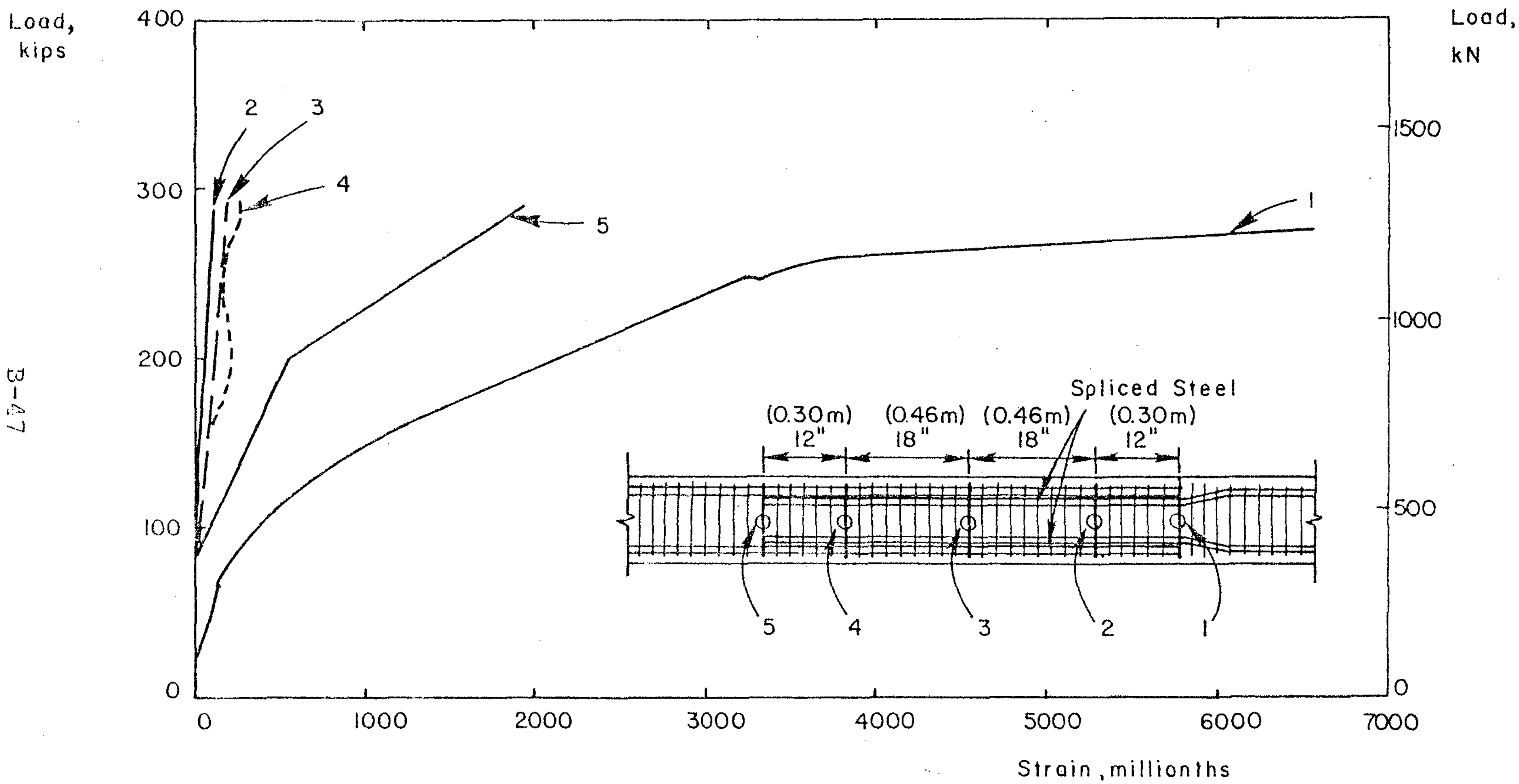


Fig. B-38 Load versus Hoop Strains for Specimen S8-1

the hoop at the offset was working to contain the outward thrust component of the offset longitudinal bars. Bursting of the concrete at the offset was more severe in Specimen S8-1 than in Specimen S6-1.

Longitudinal splitting cracks were observed at the ends of the lap, but they did not propagate along the splice. Capacity of the specimen was 330 kips (1468 kN). At this load one of the welds that anchored a longitudinal bar in the end block failed. The measured maximum load was 94% of that calculated based on average material properties.

If the weld failure had not limited capacity of this specimen, it is possible that the full calculated strength of the longitudinal reinforcement would have been developed.

Specimen S8-2

Specimen S8-2 was nominally identical to Specimen S8-1, but was subjected to six load reversals.

Load versus elongations are plotted in Fig. B-39. Initial and final crack patterns are shown in Fig. B-40.

Cracking was first observed at a load of 46 kips (205 kN). Under load reversals, cracks at the splice ends grew much wider than those at other locations, as shown in Fig. B-41.

Longitudinal steel strains are plotted as a function of applied load in Fig. B-42. Distribution of longitudinal steel strains along the splice is shown in Fig. B-43. The strain distribution and yield penetration in Specimen S8-2 were similar to those observed in the monotonic test of S8-1. It is

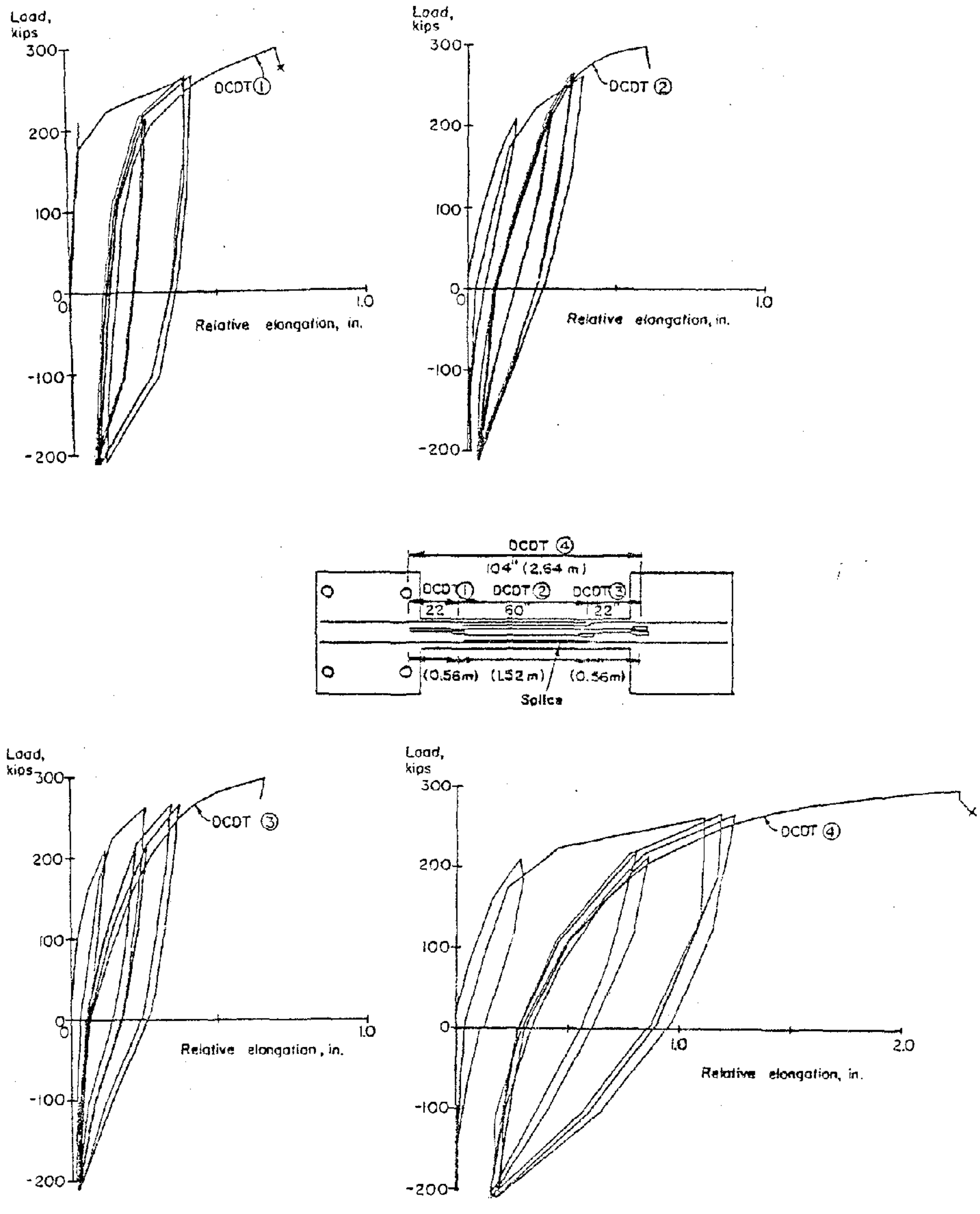


Fig. B-39 Axial Deformations of Specimen S8-2

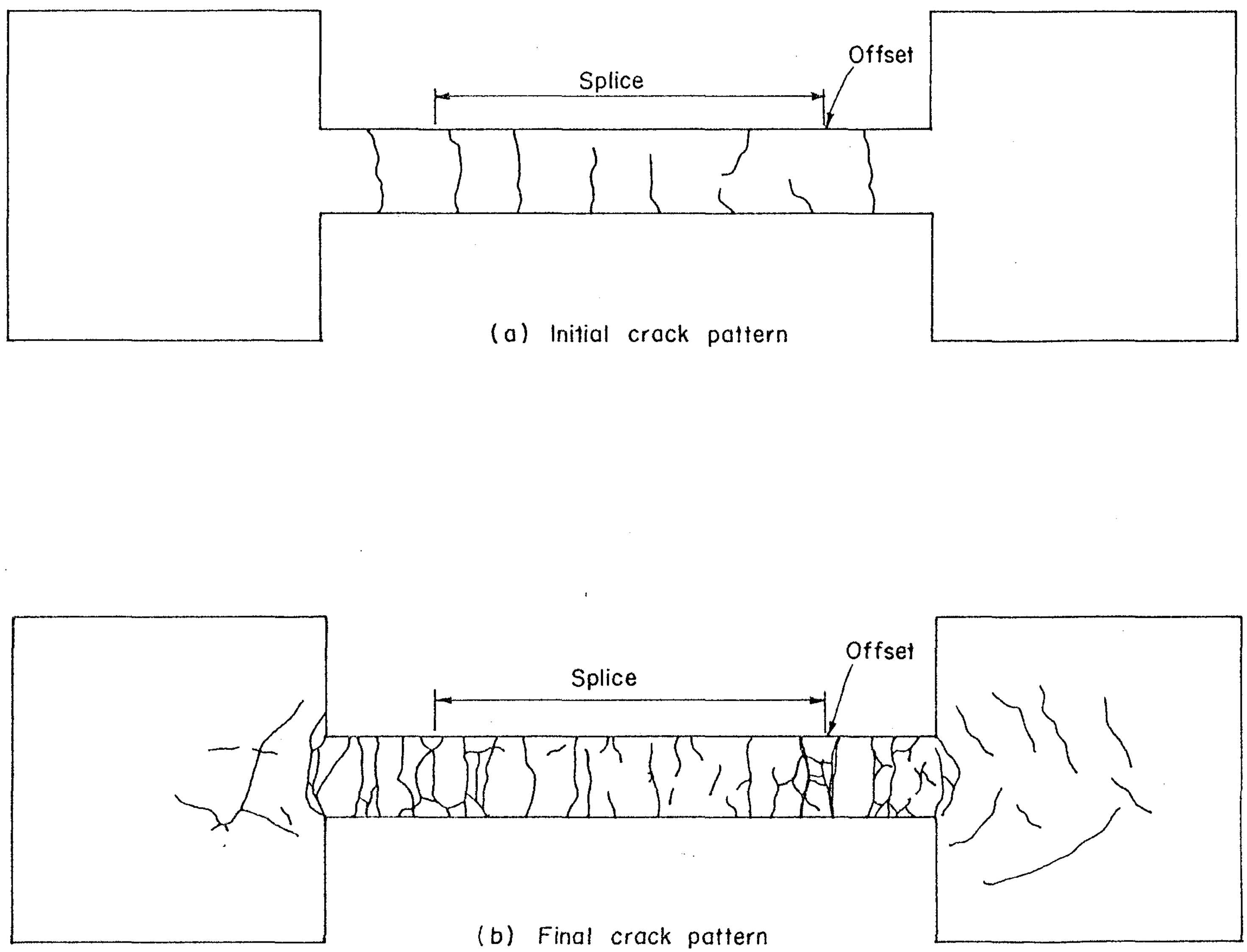


Fig. B-40 Crack Patterns of Specimen S8-2

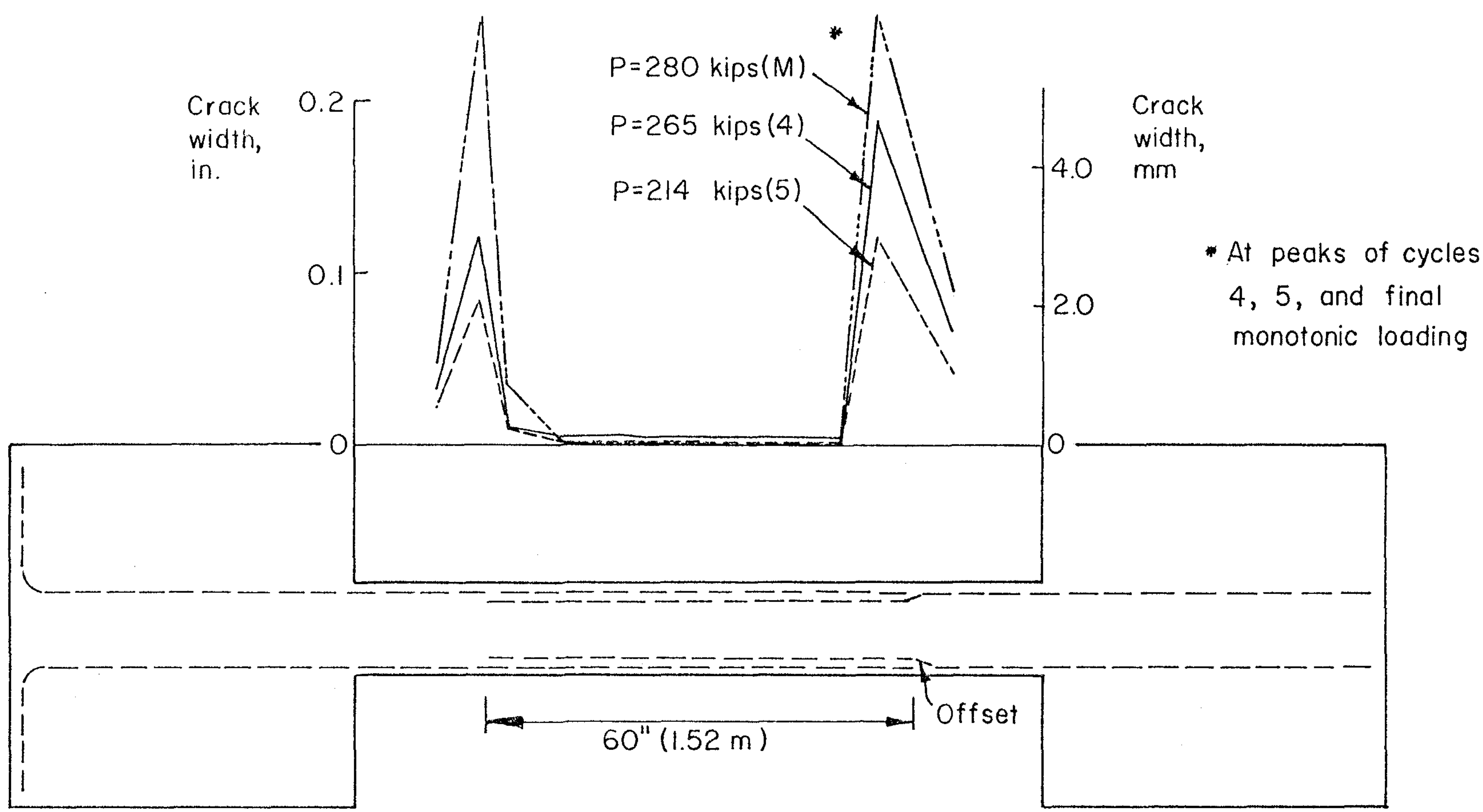


Fig. B-41 Measured Crack Widths in Specimen S3-2

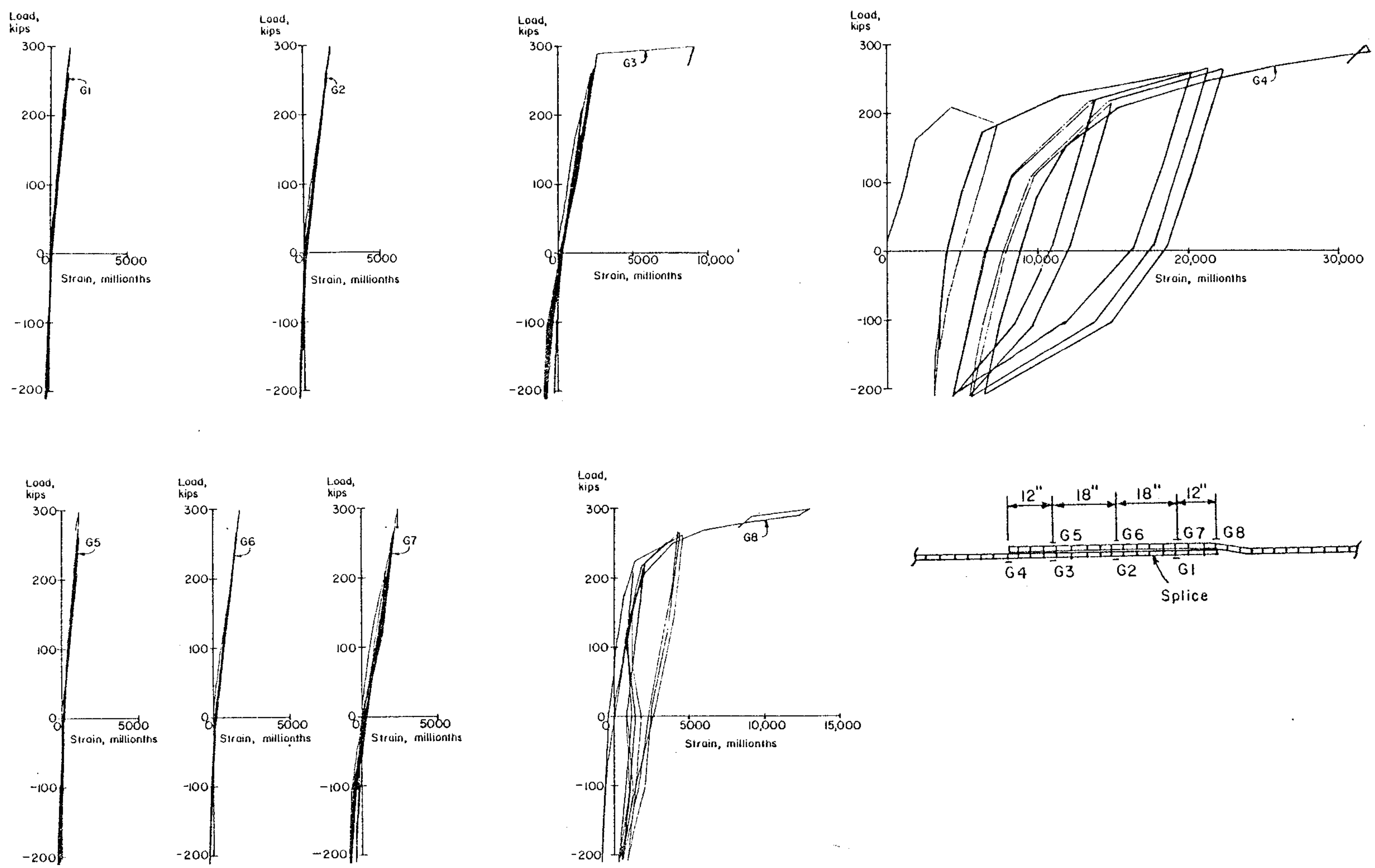
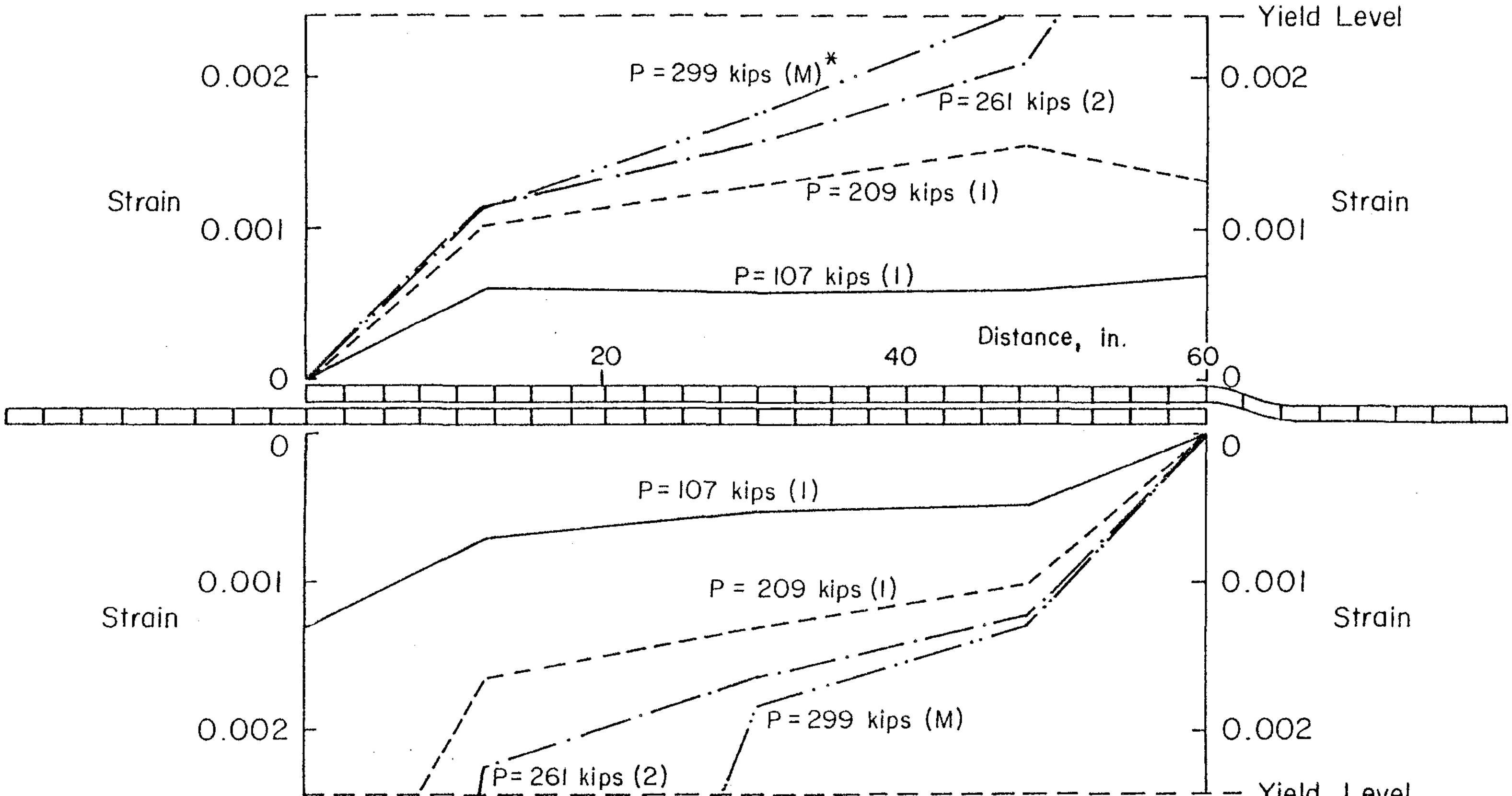


Fig. B-42 Load versus Steel Strains for Specimen S8-2



* At cycle 1 and 2, and final Monotonic loading

1 kip = 4.448 kN

Fig. B-43 Strain Distribution Along Splice of Specimen S8-2

interesting to note that in Specimen S8-2 a greater yield penetration occurred at the straight end of the splice than at the offset end.

Figure B-44 contains load versus strain curves for the transverse reinforcement. Strains indicate that only hoops at the offset end region were effective.

At a load of approximately 163 kips (725 kN) splitting cracks were observed at the offset. These cracks did not propagate along the splice. Maximum load applied to the specimen was 325 kips (1446 kN). Because the test apparatus became unstable, loading was discontinued during the monotonic increment that was being applied after the six load reversals.

Observed behavior of Specimens S8-1 and S8-2 indicated that the applied reversing load history did not have a significant effect on strength or performance.

Specimen S8-3

Specimen S8-3 was nominally identical to Specimens S8-1 and S8-2 except for the amount of confinement. Confinement in Specimen S8-3 corresponded to the maximum spacing of column ties according to the 1976 Uniform Building Code[2] and the 1977 ACI Building Code.[1]

Load versus elongation curves are plotted in Fig. B-45. Initial and final crack patterns are shown in Fig. B-46.

Cracking was first observed at a load of 46 kips (205 kN). At a load of 60 kips (267 kN), cracks were observed every 12 in. (305 mm). This spacing coincided with the location of

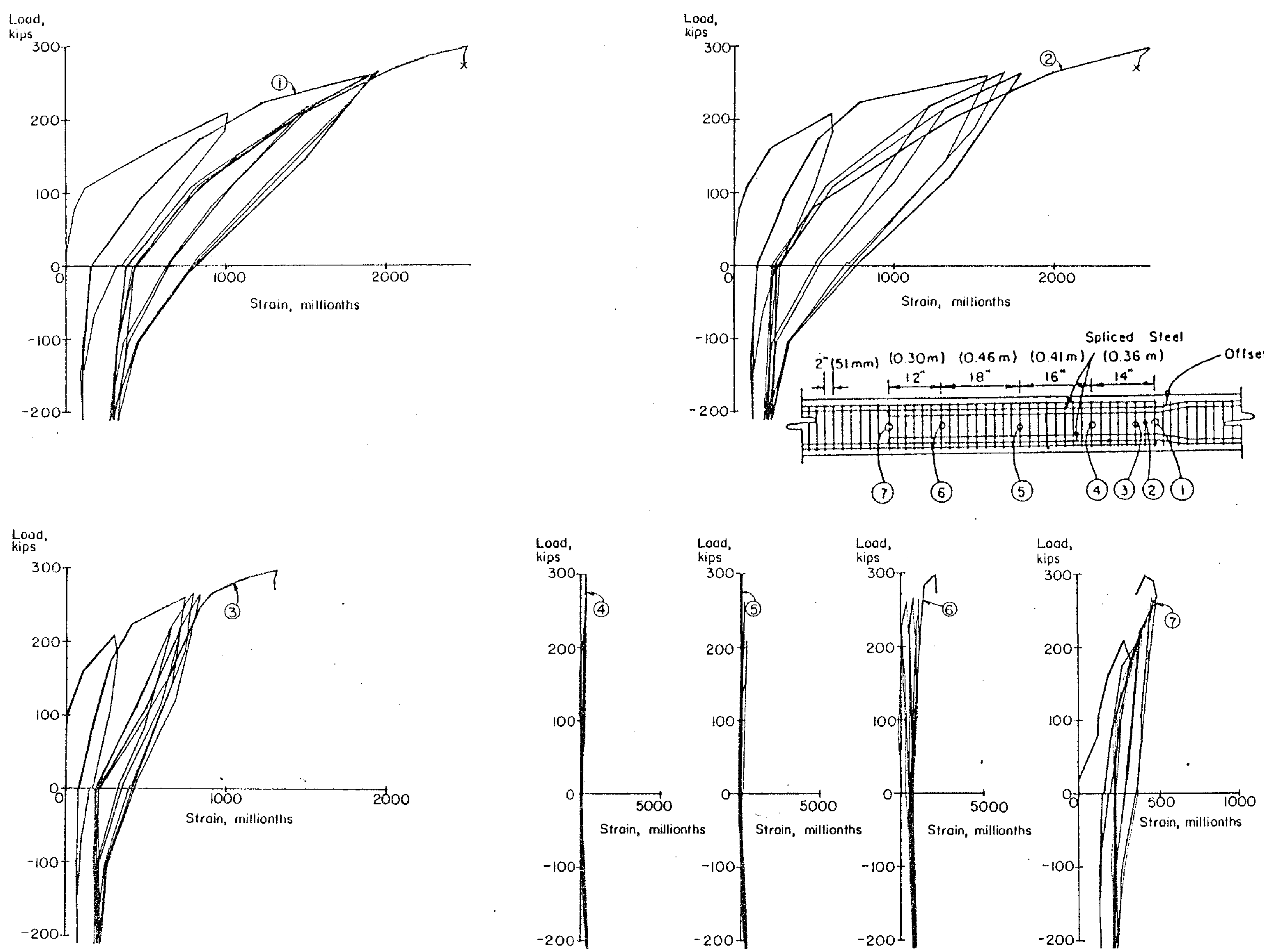
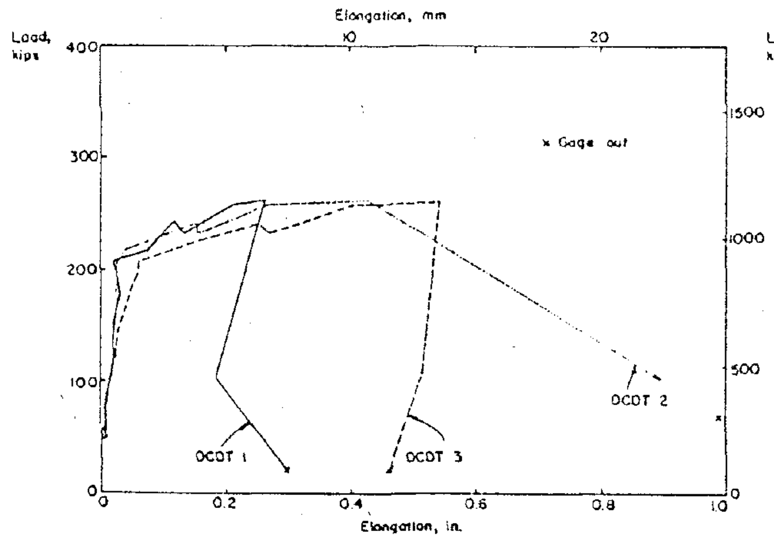
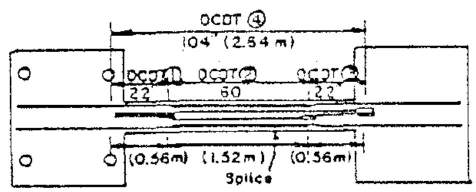


Fig. B-44 Load versus Hoop Strains for Specimen S8-2





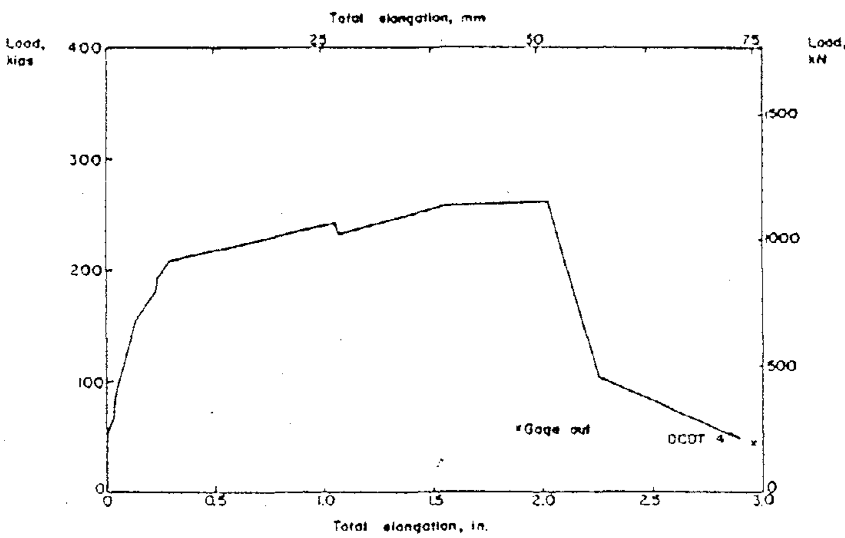


Fig. B-45 Axial Deformations of Specimen S8-3

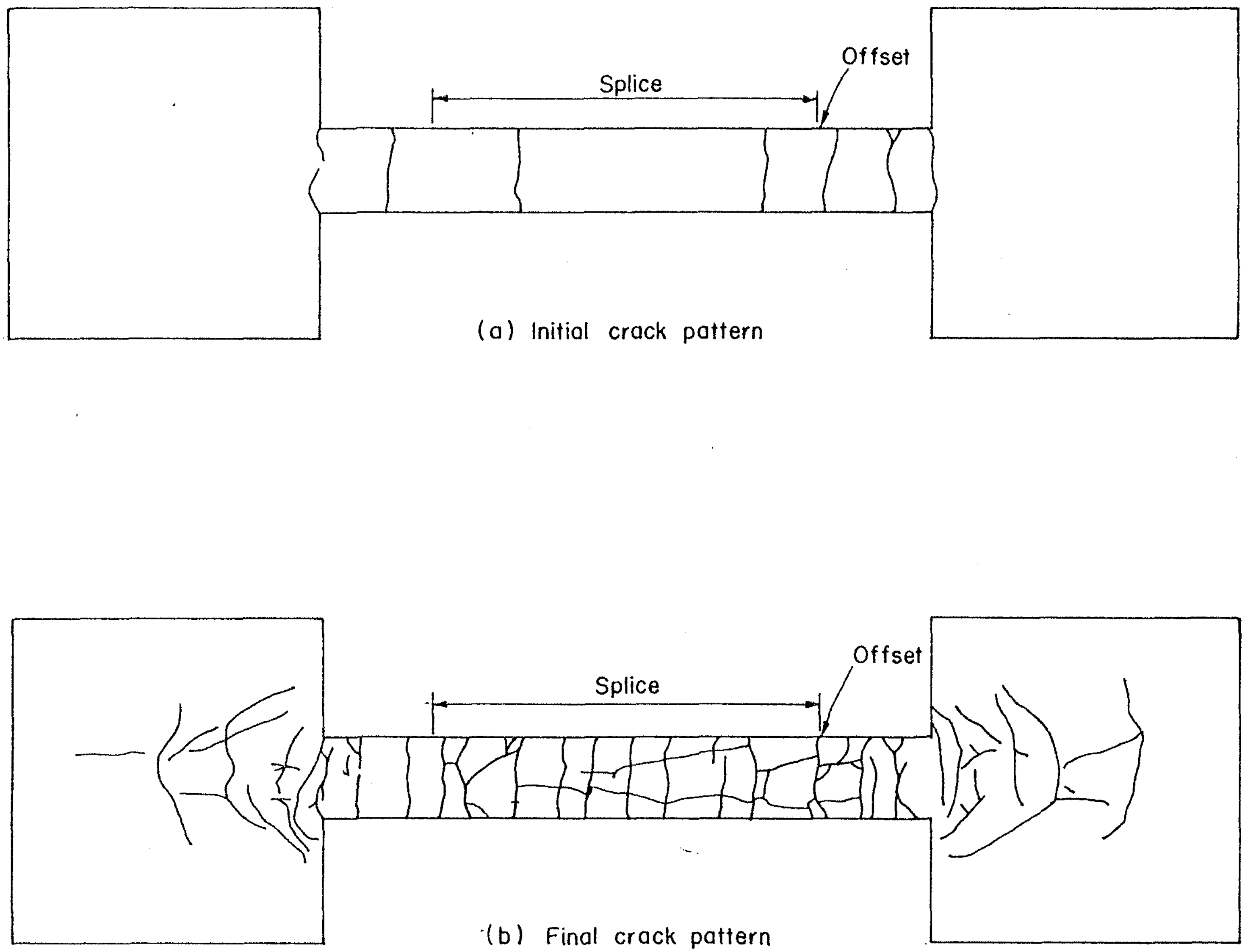


Fig. B-46 Crack Patterns of Specimen S8-3

transverse hoops. Cracks at the ends of the splice grew much wider than those at other locations as shown in Fig. B-47.

Initial yielding in spliced reinforcement occurred at a load of 211 kips (939 kN). Measured longitudinal strains are plotted in Figs. B-48 and B-49. As expected, a greater yield penetration occurred in this specimen than in Specimens S8-1 and S8-2, particularly at the offset end region.

Figure B-50 shows load versus strain curves for the hoop reinforcement. Hoops at the straight end region were subjected to higher strains than those at the offset end region.

At a load of 114 kips (507 kN), splitting cracks were observed at the offset. As load was increased, splitting cracks penetrated the splice. Capacity of the specimen was 280 kips (1245 kN). At this load, bars pulled out at the straight-end region of the splice. The behavior of Specimen S8-3 indicated that minimum column hoop reinforcement was not sufficient to prevent splice failure. Additional reinforcement concentrated at the ends of the splice might have been sufficient to develop the strength of the bars.

<u>Specimen S8-4</u>

Specimen S8-4 was identical to S8-1 and S8-2 except for the amount of hoop reinforcement. This was reduced to 50% of that required by the 1976 UBC Building Code.[2]

Load versus elongtion curves are plotted in Fig. B-51. Initial and final crack patterns are shown in Fig. B-52.

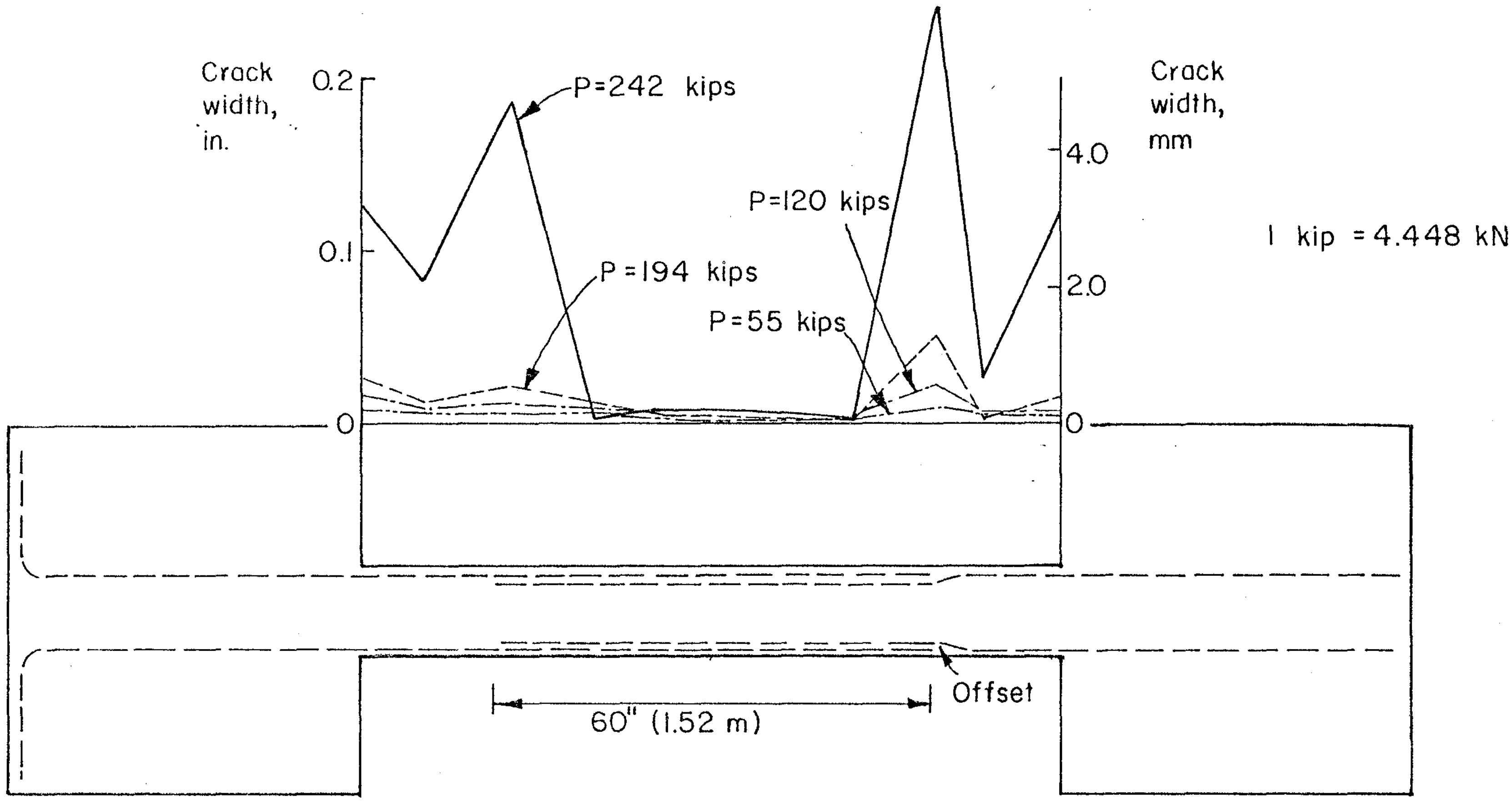


Fig. B-47 Measured Crack Widths in Specimen S8-3

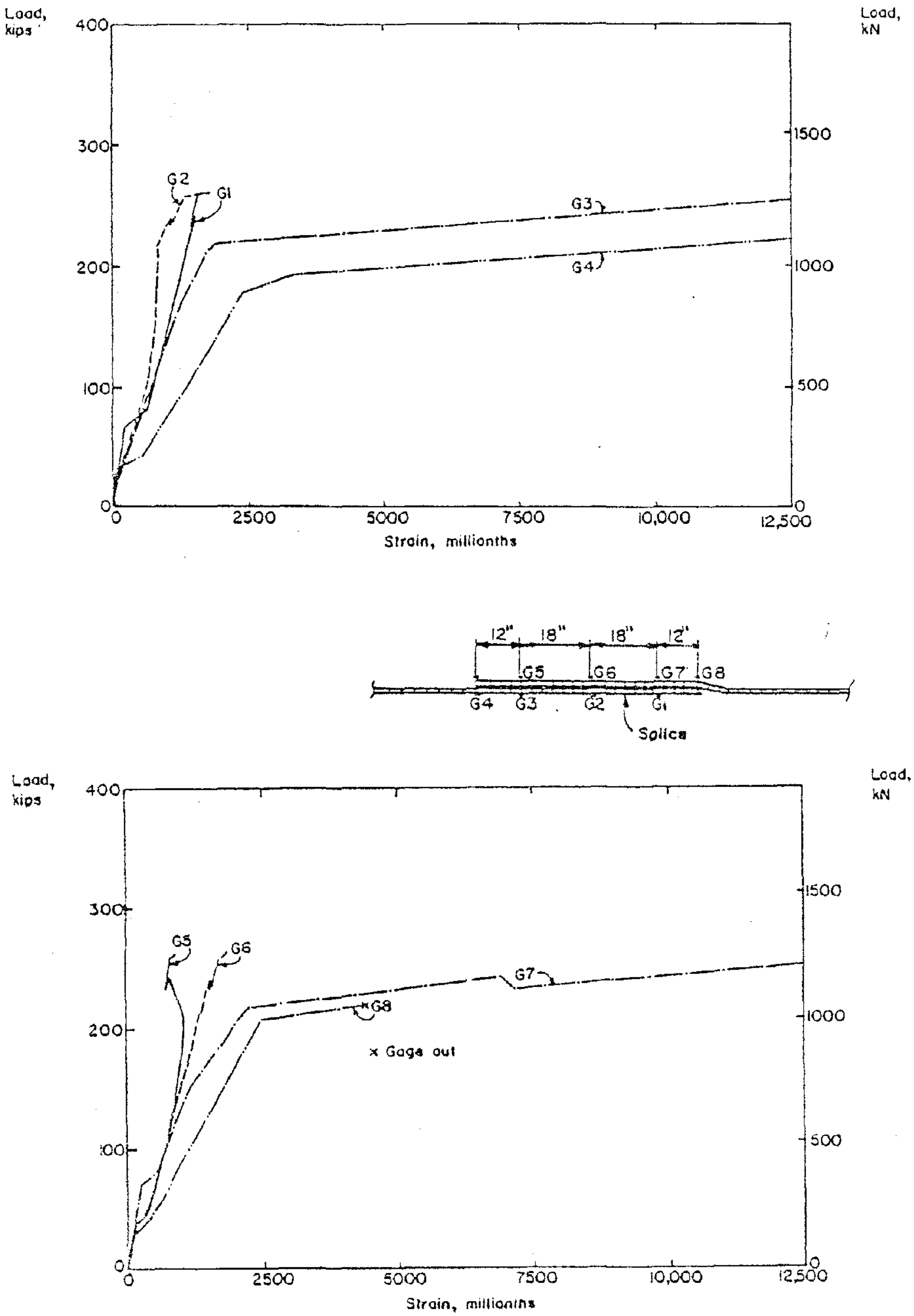
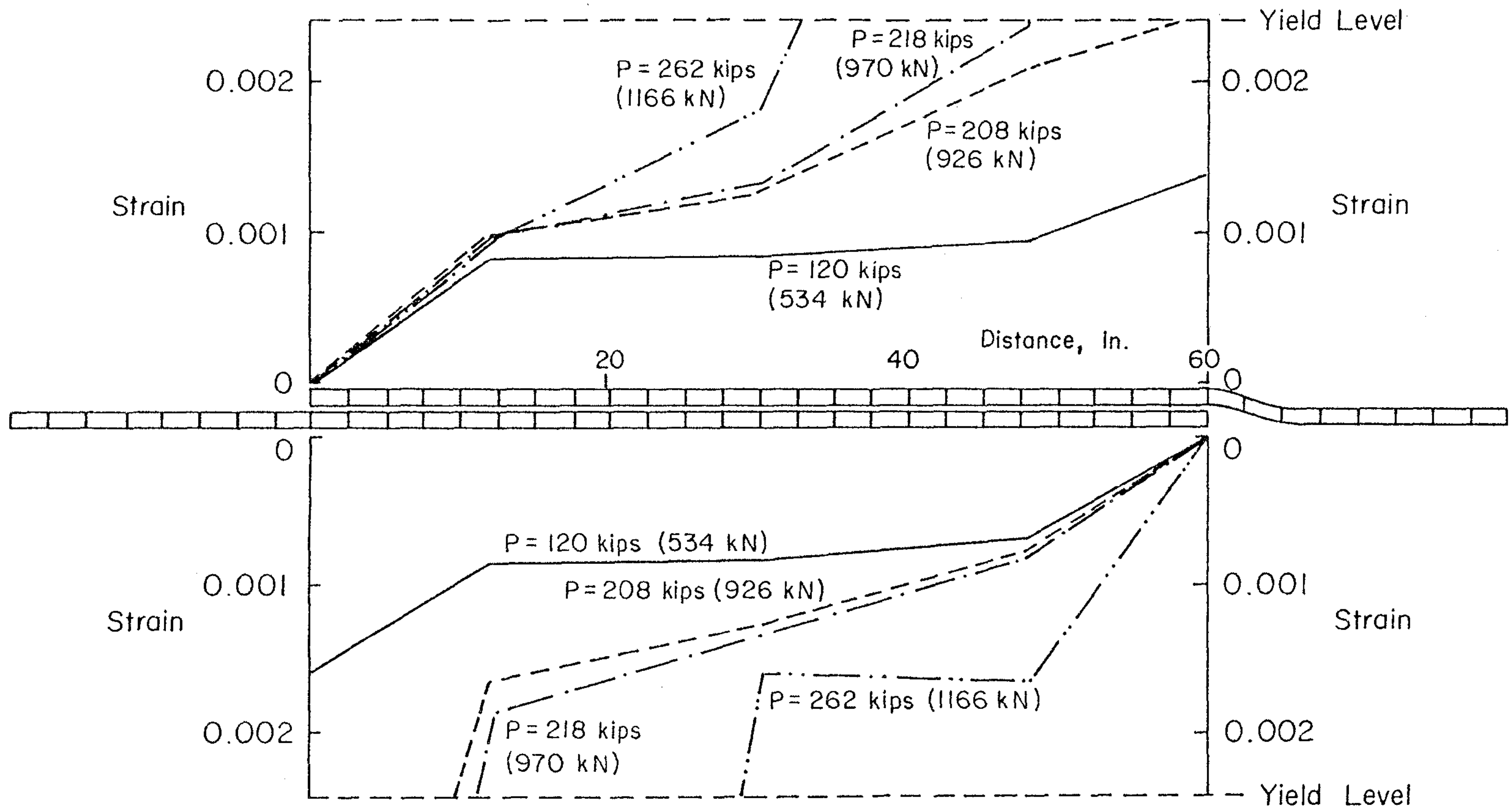


Fig. B-48 Load versus Steel Strains in Splice of Specimen S8-3



1 kip = 4.448 kN

Fig. B-49 Strain Distribution Along Splice of Specimen S8-3

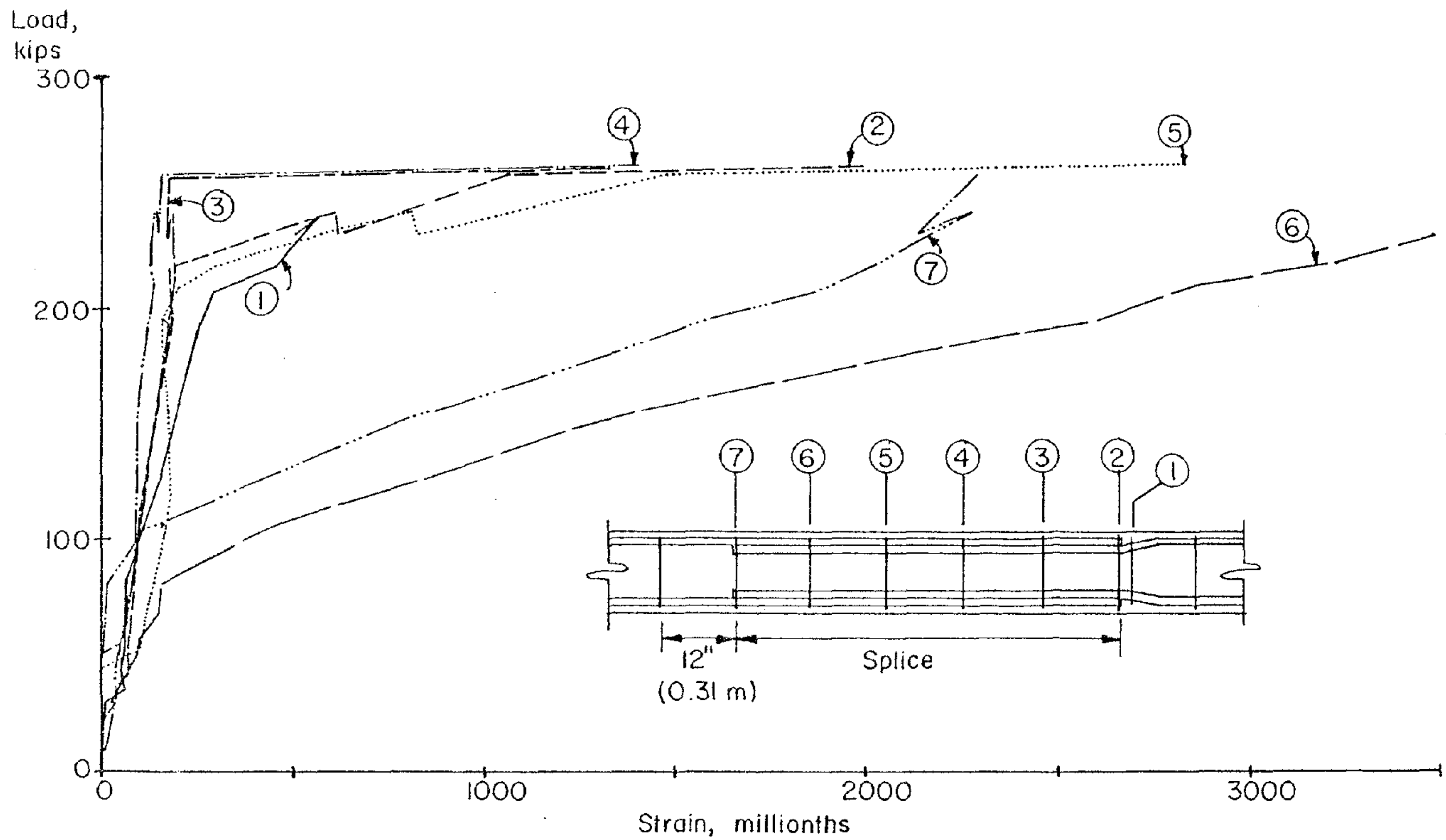


Fig. B-50 Load versus Hoop Strains for Specimen S8-3

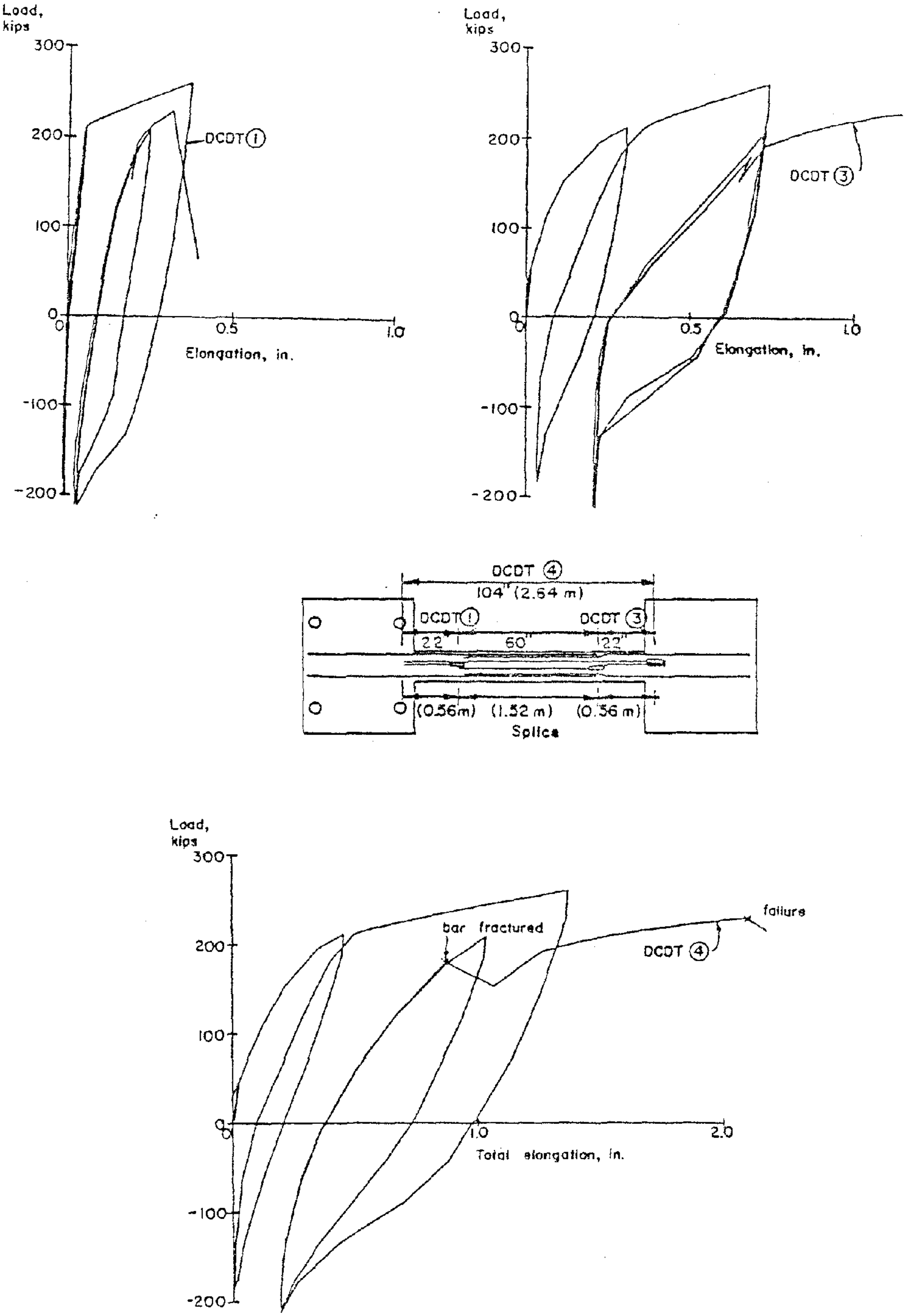
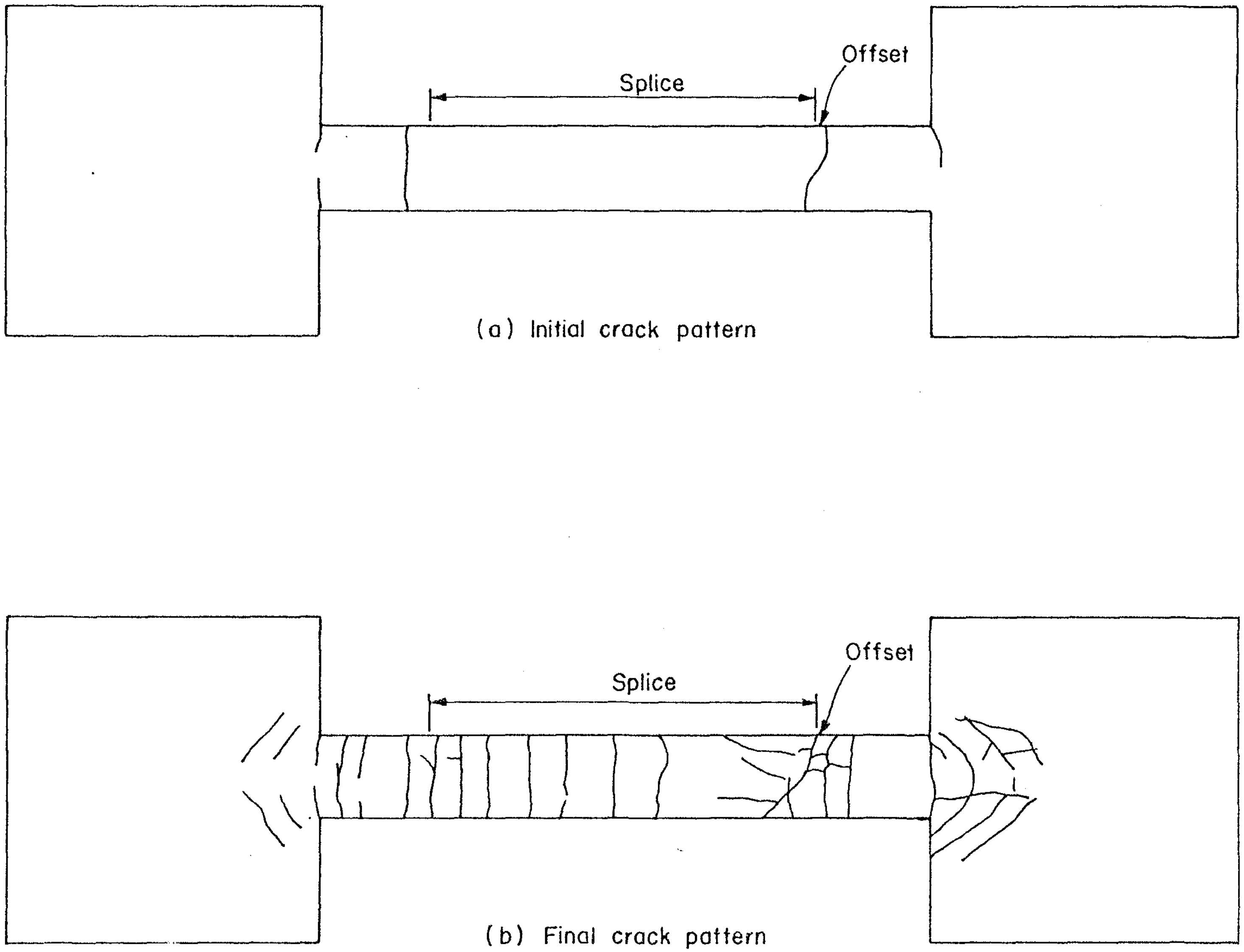


Fig. B-51 Axial Deformations of Specimen S8-4



(a) Initial crack pattern

(b) Final crack pattern

Fig. B-52 Crack Patterns of Specimen S8-4

Cracking was first observed at a load of 46 kips (205 kN). Severe spalling and bursting of concrete was observed at the first peak of first load cycle. Under increasing load, cracks at the offset grew wider than those at other location as shown in Fig. B-53.

Figures B-54 and B-55 show measured longitudinal strains. The yield penetration was similar to that observed in Specimen S8-3.

Figures B-56 and B-57 show load versus strain curves for the hoop reinforcement. It is evident that hoops at the offset region were effective.

Longitudinal splitting cracks were observed at the offset at a load of 261 kips (1161 kN) during the first peak of the second load cycle. The splitting cracks did not propagate along the entire splice length. At the end of the third load cycle, the specimen was severely damaged at the offset end region. In the first half of the fourth cycle, load carrying capacity was lost by fracture at the offset of one of the spliced bars. This may have been related to the bend in the bar at the offset. With only three bars remaining, load on the specimen was 235 kips (1046 kN). This is 90% of that calculated for three bars based on average material properties.

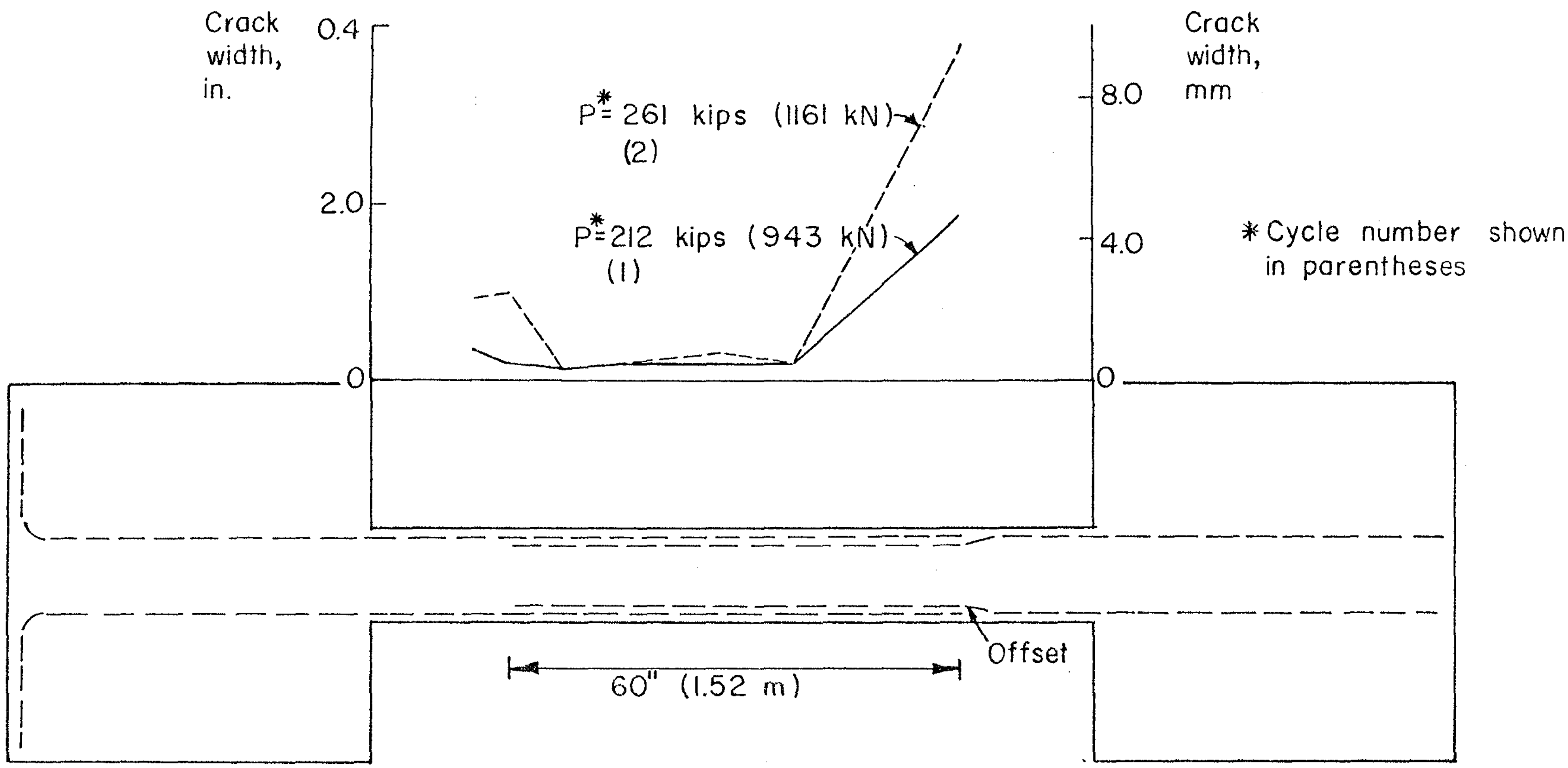


Fig. B-53 Measured Crack Widths in Specimen S8-4

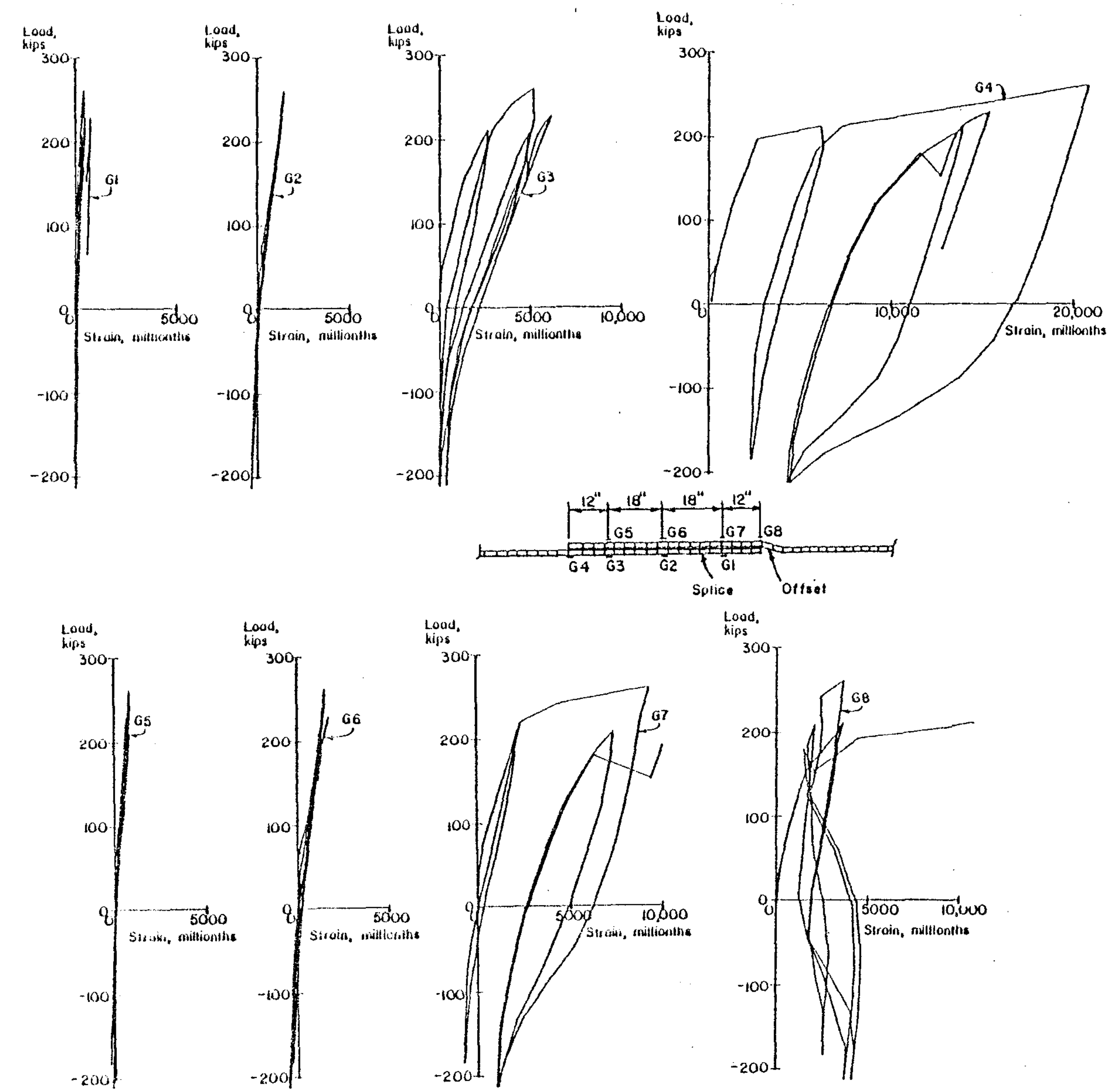
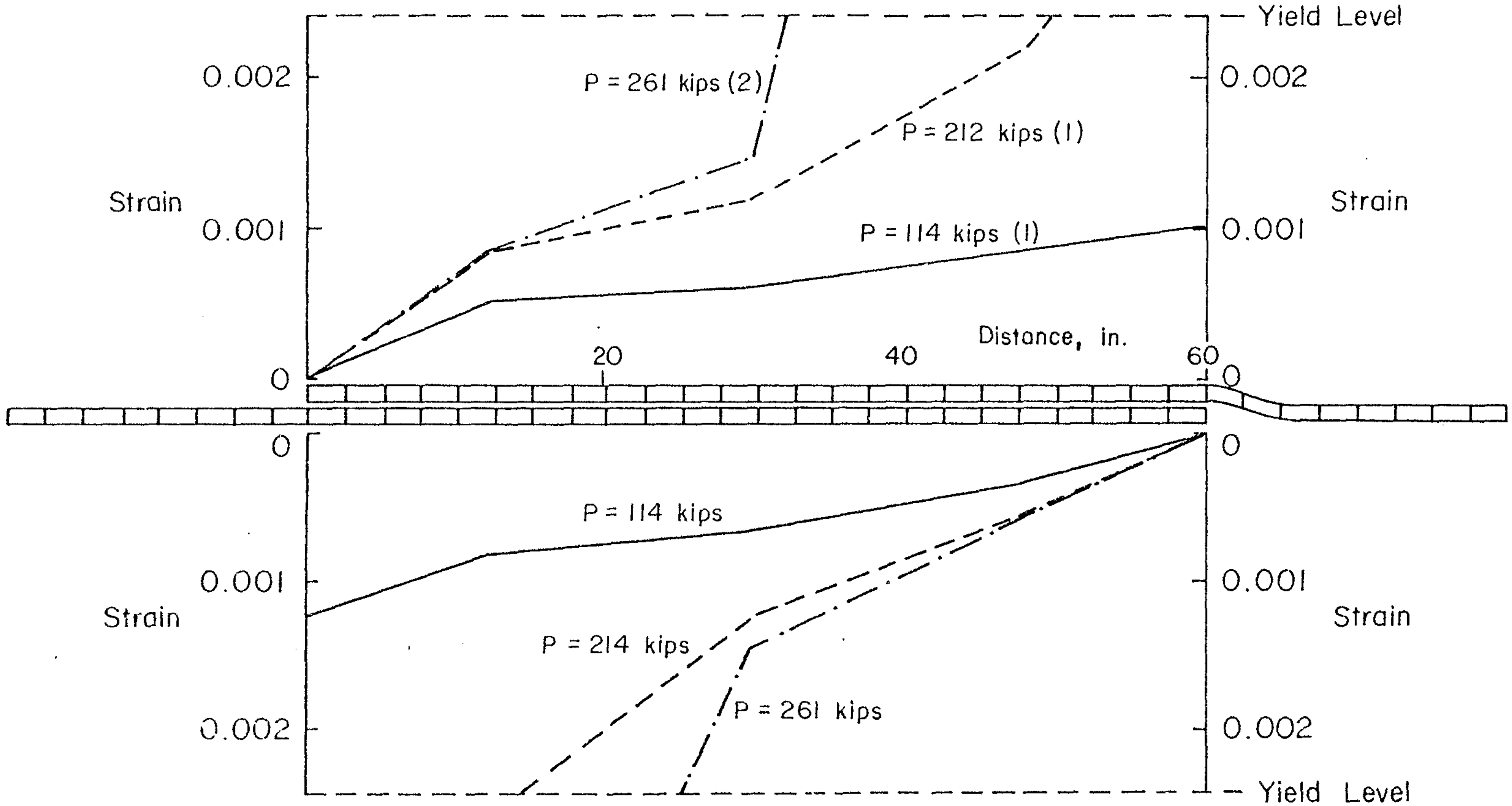


Fig. B-54 Load versus Steel Strains in Bars for Specimen S8-4



1 kip = 4.448 kN

Fig. B-55 Strain Distribution Along Splice of Specimen S8-4

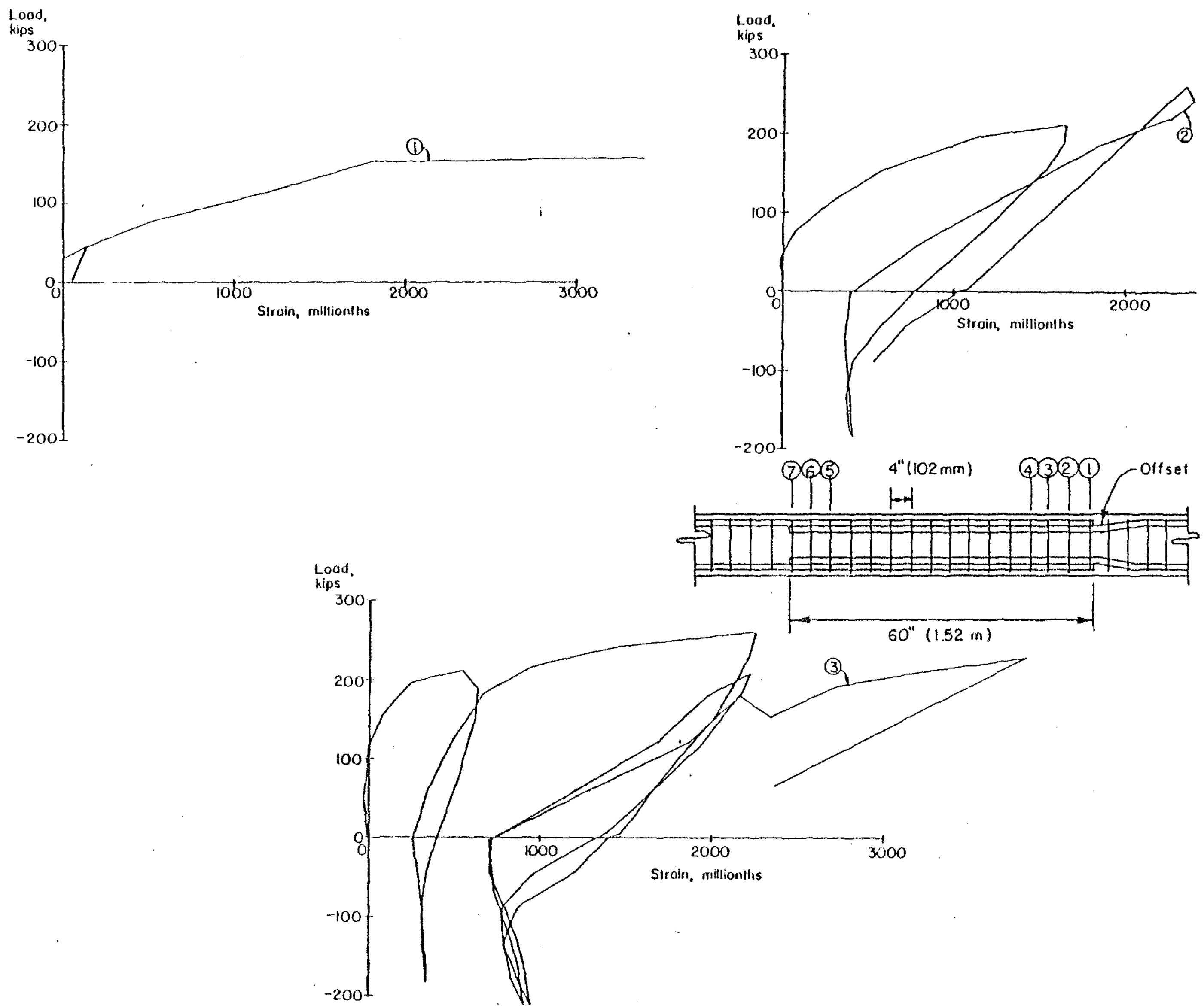


Fig. B-56 Load versus Hoop Strains for Specimen S8-4: Gages 1, 2, and 3

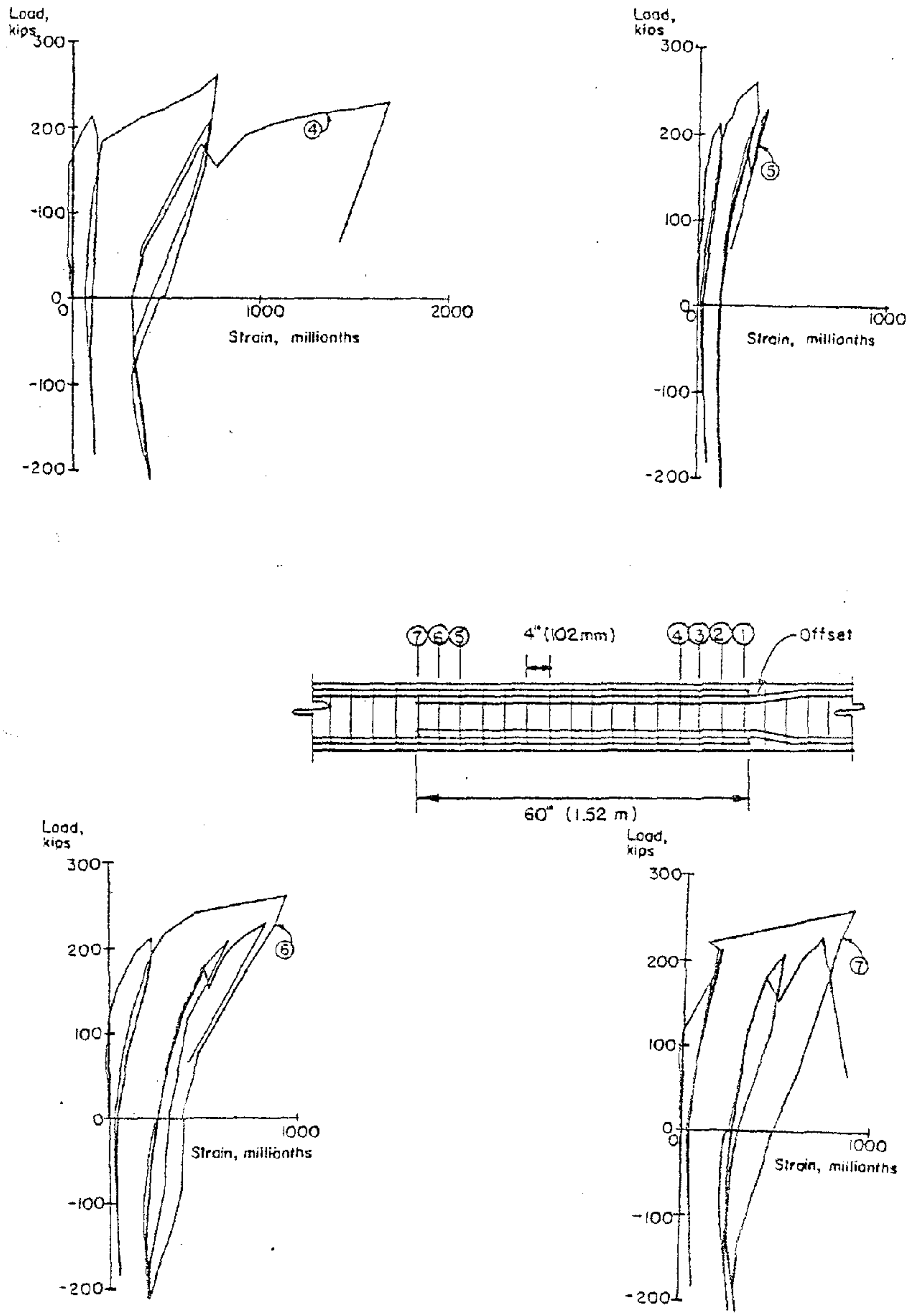


Fig. B-57 Load versus Hoop Strains for Specimen S8-4: Gages 4, 5, 6, and 7