SEISMIC DESIGN OF LAPPED SPLICES IN REINFORCED CONCRETE

Peter Gergely(I)

Richard N. White(II)

SUMMARY

The inelastic behavior and strength of lapped splices in reinforced concrete were investigated experimentally with 32 full-scale and 8 half-scale beams. The main variables were the amount and distribution of transverse reinforcement (stirrups) and the load history. The study showed that it is possible to design lapped splices to sustain a few dozen repeated loadings beyond yield if closely spaced stirrups are used over the entire length of the splice which is at least 30 bar diameters long. The effects of the presence of shear and fully reversed high-level loading were also examined to a limited extent.

INTRODUCTION

An experimental and analytical investigation of the behavior of lapped splices began at Cornell University in 1978. The primary emphasis has been on repeated loading into the inelastic range to provide information for the design of splices for severe earthquake forces. Little information was available on the subject before the beginning of this investigation.

Several researchers established that high level repeated and reversed loading produces bond deterioration and hence may significantly increase the bond capacity of deformed bars (Bresler and Bertero 1968, Takeda, Sozen, and Nielsen 1970, and Hassan and Hawkins 1977). Also, the influence of the bar or splice spacing and the transverse reinforcement was evaluated for monotonic loading (Orangun, Jirsa, and Breen 1977, ACI Committee 408 1979, and Jirsa, Lutz, and Gergely 1979). Repeated loading of splices was restricted to stresses below yield (Rehm and Eligehausen 1979 and Tepfers 1973), and it was found that splice capacity is not affected by many load repetitions below about 75% of yield.

Since information on repeated inelastic loading of lapped splices has been lacking, most seismic codes do not allow lapped splices in regions of a structure where yielding due to lateral loads may occur. Many codes, such as the ACI Building Code, require unnecessarily long splice lengths because the contribution of transverse reinforcement is not taken directly into account.

The main purpose of this investigation was to evaluate the strength and ductility of lapped splices for repeated and reversed high-intensity

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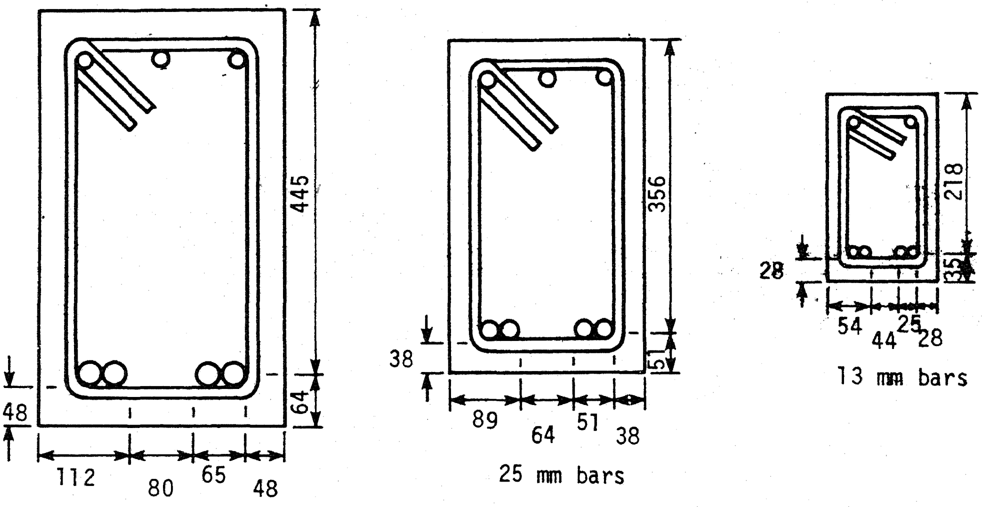
(I) Professor of Structural Engineering, and (II) Professor of Structural Engineering and Director of the School of Civil and Environmental Engineering, respectively; Cornell University, Ithaca, N.Y.

loading. The paper includes a discussion of test results, design considerations, and conclusions.

EXPERIMENTAL PROGRAM

Eight half-scale and 32 full-scale beams were tested using third-point loading. The smaller beams were 1.27 m (6 ft) long and 254 mm (10 in) deep, whereas the corresponding dimensions for the full-scale specimens were 6.40 m (21 ft) and either 406 mm (16 in) or 508 mm (20 in). Typical cross sections are shown in Fig. 1. Most splices were in the constant moment region but in a few tests they were in the shear zone.



32 mm bars

25 mm bars

13 mm bars

Fig. 1 Typical cross-sectional dimensions for beams (mm).

The main (spliced) reinforcement consisted of two 13 mm (0.5 in.) deformed bars in the small-scale tests and 25 mm (1 in.) or 32 mm (1.25 in.) deformed bars in the large-scale tests. All beams had two spliced bars at the same location and both splices were in the corners of the stirrups. All reinforcement had a yield stress of about 460 MPa (67 ksi) and the concrete had a nominal cylinder strength of 28 MPa (4000 psi).

The main variables were the amount and distribution of transverse reinforcement (stirrups) and the load history (monotonic, repeated, or reversed cyclic). Other variables studied to a limited extent were the side cover, the splice length, and the presence of shear.

One of the first questions studied was the importance of the amount of transverse steel. For monotonic loading there is a maximum effective amount of stirrups above which little contribution to splice capacity exists. It is about

$$\frac{A_{tr}}{s} = \frac{10.5d_b}{f_y} \text{ mm} \quad (\text{or } \frac{1500d_b}{f_y} \text{ in.}) \tag{1}$$

where A_{tr} is the total area of transverse steel (stirrups) crossing the expected splitting crack, s is the spacing of stirrups, d_b is the diameter of the spliced bars, and f_y is the yield stress of the stirrups (ACI Committee 408 1979, Jirsa, Lutz, and Gergely 1979).

In these tests the amount of transverse reinforcement ranged generally from about 1/3 to about twice the maximum effective amount for monotonic loading given in Eq. 1.

TEST RESULTS

The most important and interesting test results are described here. A recent report (Fagundo, Gergely, and White 1979) contains a detailed discussion of the investigation up to October 1979.

The most important question examined was the effectiveness of transverse reinforcement. As expected, it was different from the contribution of stirrups in beam splices loaded monotonically to failure. For example, for monotonic loading a second stirrup near the ends of the splice reduces the strain in the stirrups and contributes significantly to the capacity. However, for repeated loading the damage continuously spreads from the end of the splice (from both ends in the constant moment region of the beam). Therefore it is insufficient to concentrate stirrups near the ends of a splice because damage can still penetrate to the interior of the splice after load cycling near the yield level. The yield level corresponds to a flexural strain of 0.23% in these tests and the corresponding yield load is termed M_y in the following discussion. Closely spaced stirrups along the entire splice length are essential for repeated loading if the splice length is relatively short (about 30 to 35 bar diameters). Thus larger size stirrups at greater spacing are inferior to stirrups at closer spacings.

Strain gages were placed on the bottom legs and in several beams also on the vertical legs of the stirrups, near the spliced bars. These gages indicated that in beams with transverse steel not more than the amount given by Eq. 1 the stirrup strains were usually close to or above yield after several cycles in which the main bars yielded. In beams with closely spaced stirrups equal to about twice the amount in Eq. 1, the stirrup strains were below yield (typically $1/2\varepsilon_y$) even for 20 or more load cycles above M_y. This observation is significant because yielding of stirrups rapidly leads to splice failure.

The strains in the bars and in the stirrups (below the point of contact of the bars) are compared for two beams in Fig. 2. Both beams had 32 mm (1.25 in.) bars but the stirrups were twice as large in beam A (13 mm) than in beam B (9.5 mm). The latter stirrup size provides an area equal to the amount given by Eq. 1. The beams were cycled several times at 0.4 and 0.95 M_y and ten times each at 1.04 and 1.08 M_y. The strains plotted are for the fifth cycle at 1.09 M_y. The significant differences in the bar and stirrups strains are evident. Beam B failed during the seventh load repetition, whereas beam A was subjected to ten cycles each at 1.09 and 1.11 M_y without splice failure. The maximum stirrup strain was only 0.55 ε_y, though extensive splitting cracking developed.

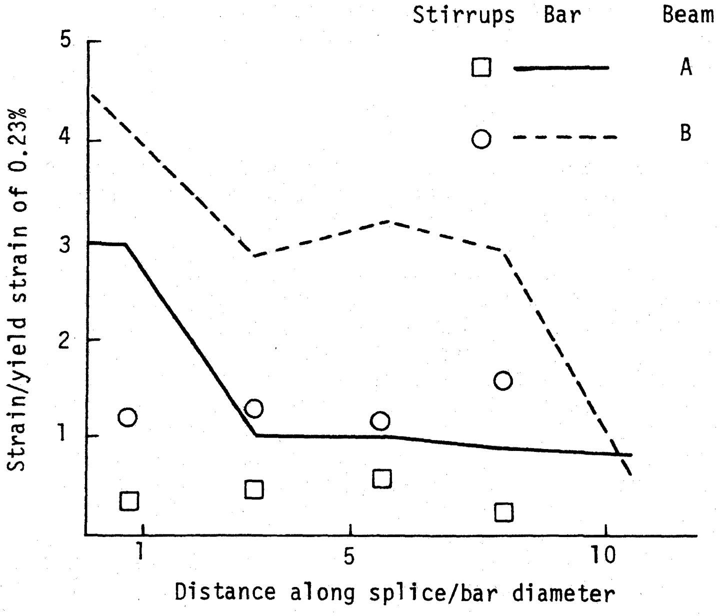


Fig. 2 Strain distribution along splice for two beams at the fifth cycle at 1.09M_y.

The tests confirmed previous findings by others that cyclic loading at less than about 80% of the yield level does not lead to failure unless a very large number of cycles are applied. Also, cycling at less than 70% of yield, which followed a single loading to about 80% yield, did not cause additional damage. As the strain in the spliced bar reaches yield, interior stirrups pick up strain at an increasing rate as damage spreads along the splice. The stirrup strains are larger for larger main bars but the relationship is not linear.

Splitting cracks generally appeared on the bottom surface at about 275 MPa (40 ksi) steel stress for beams with little transverse reinforcement and at 380 MPa (55 ksi) in beams with closely spaced stirrups equal to at least the amount given by Eq. 1. Extensive transverse and longitudinal cracks developed on the bottom face of all beams before failure. Side splitting occurred simultaneously with failure, accompanied by considerable slip of the spliced bars.

A few beams were subjected to reversed loading and compared with specimens subjected to repeated or monotonic loading. The rates of cracking, damage penetration, and strain increase were greater for reversed cyclic loading. The number of cycles before failure was always significantly less than for similar beams with repeated loading. The number of cycles and the maximum displacement at which the beams were cycled are compared in Table 1 for seven beams. Identical beam numbers signify identical beams. It is seen that load reversal reduces the number of cycles before failure. The number of cycles that can be achieved with closely spaced stirrups is significant and may be sufficient in many design situations. Note, that none of the beams with reversed loading reached twice Δ_y and all beams experienced splice failures.

The increase of stirrup strains due to cycling at a certain load was greater for reversed loading than for repeated loading. The difference was especially noticeable at high longitudinal bar stresses. The maximum stirrup strain was less than $0.75\varepsilon_y$ and the maximum bar strains were 3 to $5\varepsilon_y$. The investigation of the effects of load reversal is continuing.

Several beams had splices in the shear span of the beams. In general, these beams behaved much better than similar beams with splices in the constant moment region. All six of these beams had stirrups equal to the amount given by Eq. 1, and none of the beams experiences splice failure, but splices of identical design in the constant moment region did fail.

The amount of transverse reinforcement used for the splices was much more than what is normally required for shear. The maximum nominal shear stress was about 1.24 MPa (180 psi). Unfortunately, it is not possible to achieve a much higher level of shear because the splice would not fit in a smaller shear span.

The explanation for the much better performance of splices in the shear zone is that the moments at the two ends of the splice are not equal and therefore damage penetrates primarily from one end. In these tests the smaller moment was about half the moment at the other end of the splice and damage was evident only at the highly stressed end of the splice. The study of the effect of shear is continuing; some of the experiments planned will involve narrower beams with smaller side covers and higher shear stresses.

Table 1. Comparison of Repeated and Reversed Loading

Beam	Bar Size	Load History	Transverse Steel	Number of Cycles Above 90% Yield	Number of Cycles at Highest Displacement
1a	10	rep.	1.2	36	6 at 90 mm
1b		rev.		10	6 at 46 mm
2a	8	rep.	1.1	12	6 at 117 mm
2b		rev.		11	5 at 90 mm
2c*		rev.		21	12 at 76 mm
3a	10	rep.	2.1	45	9 at 90 mm
3b		rev.		20	10 at 58 mm

Bar size: 8 - 25 mm, 10 - 32 mm

Transverse steel is expressed as a multiple of the amount given by Eq. 1

The yield deflection was about 50 mm (2 in.) and 46 mm (1.8 in.) for beams with size 8 and size 10 bars, respectively.

DESIGN CONSIDERATIONS

Based on the test results and on simplified analysis of the force transfer at splices (Fernando, Gergely, and White 1979), a minimum amount of transverse reinforcement for repeated loading is recommended for beams made with Grade 60 reinforcement:

$$\frac{A_{tr}}{s} = \frac{d_b}{20} \tag{2}$$

The splice length should be at least 30 bar diameters. The concrete cover to the center of the bars should be at least $1.75d_b$. With this amount of transverse reinforcement, the maximum strain in the main bars will be at least $3\varepsilon_y$ (about 0.7%), which corresponded to twice the yield deflection in the beams tested in this study.

According to a recent code proposal for nonseismic design (ACI Committee 408 1979), the required lengths for straight bar development and for splices are the same for the same net spacings and covers. This recommendation was based on a statistical study (Orangun, Jirsa, and Breen 1977). The current tests indicate that this is valid for splices with relatively little confinement by transverse reinforcement or by cover, because then the splice fails when one spliced bar begins to lose its anchorage as stirrups become overstressed at the ends of the spliced bars. However, in splices with ample confinement, especially for repeated loading situations, there is a redistribution of forces well before failure. In such cases the force variation is nearly linear in both spliced bars and

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*Beam 2c was subjected to a greater number of cycles at a lower level, 0.9 M_y, than beams 2a and 2b which were cycled only above M_y.

the bond forces (thus the wedging effects) are nearly uniform. This means that the radial bursting forces produced by the two bars are superposed to a large extent and the required splice length is greater than the corresponding development length. This difference was clearly evident in the experiments as beams with little confinement failed soon after the formation of splitting cracks, whereas beams with adequate confinement sustained a number of cycles after extensive splitting.

CONCLUSIONS

Tests on full-scale beams showed the importance of the amount and distribution of stirrups on splice behavior. The rate and spread of bond deterioration is significantly affected by the amount and distribution of stirrups along the splice length.

Lapped splices can be designed to sustain repeated loading to at least $3\varepsilon_y$ (ε_y was equal to about 0.23%), which corresponds to about $2\Delta_y$ for the beams tested.

Splices must be adequately confined by uniformly spaced stirrups over the splice length. As the stresses at the ends of the spliced region approach yield, the bursting forces generated by the spliced bars tend to be uniformly distributed along the splice length.

For splices of at least 30 bar diameters in length subjected to a limited number of cycles up to $3\varepsilon_y$ (or about twice Δ_y) the stirrup spacing should not exceed

$$s \leq 20 \frac{A_{tr}}{d_b} \qquad (3)$$

for Grade 60 reinforcement for main bars and stirrups.

Reversed cyclic loads are significantly more detrimental to splice performance than repeated loads. The splices failed in all beams subjected to reversed cyclic loading although some sustained about a dozen cycles up to about $1.75\,\Delta_y$.

The ACI 408 proposal is adequate for splice design for monotonic loads up to yield and for repeated loads below 80% of the monotonic failure load. Unless at least the maximum amount of stirrups specified by ACI 408 is used, spliced regions will probably fail during the first hundred cycles at or above 80% of the monotonic bond failure load.

Most current structural concrete codes for seismic areas do not permit lapped splices in regions where flexural yielding or severe stress reversals are anticipated in the structure. These codes suggest that such splices are not reliable under conditions of cycling into the inelastic range. The research has indicated that such splices can be designed under certain conditions.

Preliminary results indicate that the presence of shear is not detrimental to splice capacity if the maximum recommended amount of web reinforcement for splices is used.

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