DELAYING SHEAR STRENGTH DECAY IN REINFORCED CONCRETE FLEXURAL MEMBERS UNDER LARGE LOAD REVERSALS

Charles F. Scribner[I] and James K. Wight[II]

SUMMARY

This paper describes an experimental program designed to examine the ability of intermediate layers of longitudinal reinforcement to delay strength and stiffness decay in a reinforced concrete beam subjected to alternating displacements several times larger than the yield displacement. Fourteen T-shaped specimens were constructed and loaded to destruction. It was determined that gross shear stress was the most significant factor influencing total energy dissipation capacity of a flexural member. Intermediate longitudinal reinforcement was most effective in delaying shear strength and stiffness decay in beams with maximum gross shear stresses between 0.25 and $0.50\sqrt{f'_c}$,MPa (3 and $6\sqrt{f'_c}$,psi).

TEXT

Introduction. Flexural members which make up the lateral load resisting system of a concrete structure bear a universal caveat: flexural capacity must not be reduced by local shear failures. The task of designing members which will remain elastic is not difficult and involves only the normal assignment of shear forces to concrete and steel. This procedure has no guarantee of success for members which may undergo repeated inelastic flexure due to earthquake loads however, as the region of the flexural member which undergoes repeated inelastic rotation becomes segmented and broken into many discrete chunks. The codes governing American concrete design practices (1,4) recognize this problem by requiring increased amounts of transverse reinforcement in member regions likely to suffer inelastic flexure during earthquake loading. It has been suggested, however, that transverse reinforcement may not be adequate to satisfactorily limit shear strength decay in cyclically flexed members. The purpose of this investigation was to study the use of two layers of intermediate longitudinal reinforcement in reducing shear strength decay in members subjected to repeated reversed inelastic flexure.

The problem of strength decay has received much consideration. Brown and Jirsa (3) noted the formation of planes of shear slippage nearly perpendicular to member longitudinal axis during cyclic flexural loading and questioned the ability of transverse reinforcement at any spacing to limit sliding along such planes. Wight and Sozen (7) also saw shear strength deterioration in members with constant axial load and various amounts of transverse reinforcement. Paulay (5) and, later, Bertero and Popov (2) used reinforcement diagonally crossing the region of inelastic flexure to effectively prevent strength decay for beams having very high shear stresses.

[I] Assistant Professor of Civil Engineering, University of Illinois, Urbana

[II] Associate Professor of Civil Engineering, University of Michigan, Ann Arbor.

Experimental program. Fourteen T-shaped beam and column subassemblies were constructed and tested at the University of Michigan (6). The general specimen configuration is illustrated in Fig. 1, with specimen dimensions listed in Table 1. In general, odd-numbered specimens contained only transverse reinforcement, while even numbered specimens contained intermediate layers of longitudinal reinforcement in addition to transverse reinforcement. The position of transverse reinforcement,omitted for clarity in Fig. 1, satisfied spacing requirements of the ACI Building Code, 318-77 (1) in the region of inelastic flexure. Other major variables included shear span to depth ratio (varying from 3.6 to 5.0), main longitudinal reinforcement ratio (varying between 1.27 and 6.62 percent), and percentage of transverse reinforcement, which varied from 0.63 to 1.75 percent.

Specimens were designed to cover the range of shear stress values from $0.17\sqrt{f'_c}$, MPa ($2\sqrt{f'_c}$, psi) to greater than $0.5\sqrt{f'_c}$, MPa ($6\sqrt{f'_c}$, psi). Pairs of specimens 1 and 5, 2 and 6, 9 and 11 and 10 and 12 contained identical reinforcement and were tested at different shear spans to determine the effect of differing shear stresses on cyclic performance.

Intermediate longitudinal reinforcement was chosen so the total area of intermediate bars would be approximately one-quarter the area of main tension reinforcement. The actual ratio of areas for each specimen is given in Table 1. The larger amount of intermediate longitudinal reinforcement used in Specimen 14 represented a significant design variation. Intermediate reinforcement extended into the beam a distance equal to twice the beam effective depth plus an extension of twelve bar diamaters, a length which was expected to traverse the zone of inelastic hinging.

Although two general sizes of specimen were tested, test procedure remained constant. In each case, the column portion of the specimen was held firmly by roller bearings and an axial column load was applied and held constant for the duration of the test. The beam tip was then slowly deflected by a hydraulic ram according to the displacement pattern shown in Fig. 2. Displacement ductility, defined as the ratio of beam load point displacement at any stage in testing to the corresponding displacement at initial yield of the beam tension reinforcement under positive shear, was used as the displacement control parameter. Member torsional instability or failure to resist displacement constituted cause for termination of loading prior to completion of the normal testing routine.

Test results. Several aspects of behavior were common to all specimens. All beam-column joints developed at least one diagonal crack, but no motion was observed along any joint crack and measured strain in joint ties never exceeded yield strain. No cracks were noted in the columns outside the joint region. Beam behavior outside the plastic hinging zone was also similar for all specimens. Although cracks formed in almost all beams between the point of load application and the zone of inelastic hinging, no sliding or deterioration was noted along any of these cracks.

All specimens experienced failure or major deterioration as a result of cracking and crushing of concrete in the beam hinging zone, which was considered to extend from the face of the column a distance equal to overall beam depth. The nature, rate and extent of deterioration varied greatly from one specimen to another. Vertical and inclined cracks which formed during a loading half-cycle were intersected by similar types of cracks which originated from the opposite side of the beam during loading reversal.

Discussion of specimen behavior. It is convenient to discuss the behavior of the specimens examined in this test series by considering three groups based on maximum first-cycle shear stress. Shear stress values of $0.25\sqrt{f'_c,\text{MPa}}$ ($3\sqrt{f'_c,\text{psi}}$) and $0.5\sqrt{f'_c,\text{MPa}}$ ($6\sqrt{f'_c,\text{psi}}$) were used as the points of separation for the three groups. A grouping of this nature was considered appropriate for two reasons. First, shear stress was the most important single factor in defining the general response of the members to repeated reversed loading. Second, it was found that intermediate longitudinal reinforcement was most effective in preventing shear strength decay for members with maximum shear stresses between these limits.

Only Specimens 1 and 2 had maximum shear stresses less that $0.25\sqrt{f'_c}$. Both specimens showed ductile and repeating behavior for the duration of the nominal loading routine. Because shear stress was not sufficient to cause shear strength deterioration in the specimen containing only transverse reinforcement (Specimen 1), the addition of intermediate longitudinal reinforcement did not provide significantly improved performance.

Specimens 3 through 10 and 13 and 14 developed maximum shear stresses between 0.25 and $0.5\sqrt{f'_c}$. Specimens whose shear reinforcement included intermediate longitudinal reinforcement were able to dissipate an average of 27 percent more energy than comparable specimens which contained only the vertical web reinforcement required by the ACI Building Code seismic provisions (1). The increase in total energy dissipation and reduction of shear strength deterioration rate produced by the inclusion of intermediate longitudinal bars are most dramatically demonstrated by comparing the results of Specimens 3 and 4. These specimens were identical except that Specimen 4 contained longitudinal shear reinforcement in addition to the reinforcement contained in Specimen 3. The load vs. displacement curves for these two specimens are shown in Figs. 3 and 4. As comparison of the figures illustrates, Specimen 4 was able to withstand three more cycles of load at large displacement reversal than was Specimen 3, and dissipated 75 percent more energy. Intermediate longitudinal bars inhibited opening of cracks in the beam plastic hinging zone and distributed cracking throughout the zone. This resulted in decreased average crack width and decreased sliding along each crack.

Specimens 11 and 12 developed maximum shear stresses greater than $0.5\sqrt{f'_c}$ and suffered severe stiffness and strength deterioration during repeated reversed loading. The specimens were identical except that Specimen 12 contained intermediate longitudinal reinforcement. Specimen 12 survived two more cycles of reversed load than did Specimen 11 and dissipated 30 percent more energy. It must be noted that no consensus exists as to the exact requirements for acceptable performance of a member under repeated reversed loading. Although the performance of these two specimens may not have been considered acceptable previously, speculation is currently growing that perhaps the loading histories used for laboratory experimentation have been far too conservative to accurately represent the degree of inelastic rotation that a member should logically be expected to withstand. At this time, however, it must be concluded that these two specimens with very high shear stresses did not perform satisfactorily.

Specimens 7 and 13 were noteworthy in that they contained transverse reinforcement much larger than necessary for strength. The effect of such large amounts of transverse reinforcement was to concentrate damage near the face of the column (Specimen 7) and in the beam-column joint (Specimen 13). It was considered that both failures might aggrevate bond deterioration in the beam-column joint, reducing structure integrity perhaps more than would a beam shear failure. A beneficial result of very large transverse reinforcement, however, was the lateral stability supplied to main longitudinal compression reinforcement. Because eight specimens (Nos. 3,4,6,9,10,11,12,14) experienced flexural failure as a result of buckling of compression reinforcement, the benefits provided by large transverse reinforcement are significant. Criteria for tie size to prevent bar buckling should be developed independent of shear strength decay requirements.

Summary and conclusions. Fourteen reinforced concrete exterior beam-column subassemblies were tested to investigate the effect of intermediate layers of longitudinal reinforcement in preventing shear strength deterioration in flexural members subjected to repeated reversed loading. Based on the results of these tests, the following conclusions can be drawn:

1) The repeatability of hysteretic response of reinforce concrete members during reversed loading is closely linked with maximum shear stress experienced by the members. Members with maximum shear stresses less than $0.25\sqrt{f'_c}$,MPa responded primarily in flexure with little tendency to develop planes of shear slippage. Members with maximum shear stresses greater than $0.5\sqrt{f'_c}$,MPa readily developed planes of shear slippage, with resulting shear strength decay. Members with maximum shear stresses between $0.25\sqrt{f'_c}$ and $0.5\sqrt{f'_c}$ responded with a mixture of shearing and flexural action which varied with shear stress level.

2) Intermediate longitudinal reinforcement was most effective in improving hysteretic response of doubly reinforced members which developed maximum shear stresses between $0.25\sqrt{f'_c}$ and $0.5\sqrt{f'_c}$.

3) An increase in size of transverse reinforcement increased member energy dissipation, concentrated damage, and stabilized longitudinal reinforcement against buckling.

4) The buckling shapes of compression reinforcement seen in these specimens indicate that transverse reinforcement strength may be at least as significant as spacing in preventing buckling of compression reinforcement during repeated reversed loading.

ACKNOWLEDGEMENT

The reported research was sponsored by the National Science Foundation through Grant NSF ENV75-13900 and by the Horace H. Rackham School of Graduate Studies Grant FRR-387098. The conclusions are those of the authors and do not necessarily reflect the views of the sponsors.

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NOTATION

f'_c = maximum concrete compressive strength obtained from standard cylinders measuring 102 mm diam. x 204 mm high (4 in. diam. x 8 in. high)

V = force in loading ram as measured by a load cell attached between the loading ram and the beam tip

α = shear measured at maximum positive displacement in first load cycle, as a multiple of $bd\sqrt{f'_c}$, MPa

δ = deflection of point of loading ram attachment to beam tip with respect to fixed end of loading ram

TABLE 1

PHYSICAL DIMENSIONS OF SPECIMENS* AND SELECTED TEST RESULTS

Specimen Number	a (m)	h (mm)	b (mm)	Number-Bar Designation±					$\frac{A_i}{A_s}$	Max. Shear (α)+	Total Energy Absorbed (kN-m)
				A_s	A'_s	A_i	A_v	A_{vi}			
1	1.05	25.	20.	2-#6	2-#5	-	#2	-	0	0.17	41.4
2	1.05	25.	20.	2-#6	2-#5	4-#2	#2	#2	0.23	0.19	44.5
3	1.05	30.	20.	3-#6	3-#5	-	#2	-	0	0.26	35.2
4	1.05	30.	20.	3-#6	3-#5	4-#3	#2	#2	0.33	0.29	61.5
5	0.79	25.	20.	2-#6	2-#5	-	#2	-	0	0.28	35.7
6	0.79	25.	20.	2-#6	2-#5	4-#2	#2	#2	0.23	0.29	37.0
7	1.05	30.	20.	3-#6	3-#5	-	#3	-	0	0.30	46.0
8	1.05	30.	20.	3-#6	3-#5	4-#3	#2	-	0.33	0.32	57.2
9	1.52	36.	25.	4-#8	4-#7	-	#3	-	0	0.41	144.0
10	1.52	36.	25.	4-#8	4-#7	4-#4	#3	#2	0.25	0.42	154.0
11	1.22	36.	25.	4-#8	4-#7	-	#3	-	0	0.51	81.7
12	1.22	36.	25.	4-#8	4-#7	4-#4	#3	#2	0.25	0.52	106.0
13	1.52	36.	25.	4-#8	4-#7	-	#5	-	0	0.38	227.0
14	1.22	36.	25.	3-#8	3-#7	4-#5	#3	#2	0.52	0.40	143.0

* Dimensions illustrated in Fig. 1.

+ Maximum shear measured at maximum positive displacement in first load cycle, as a multiple of $bd\sqrt{f'_c}$,MPa.

± U.S.A. bar sizes.

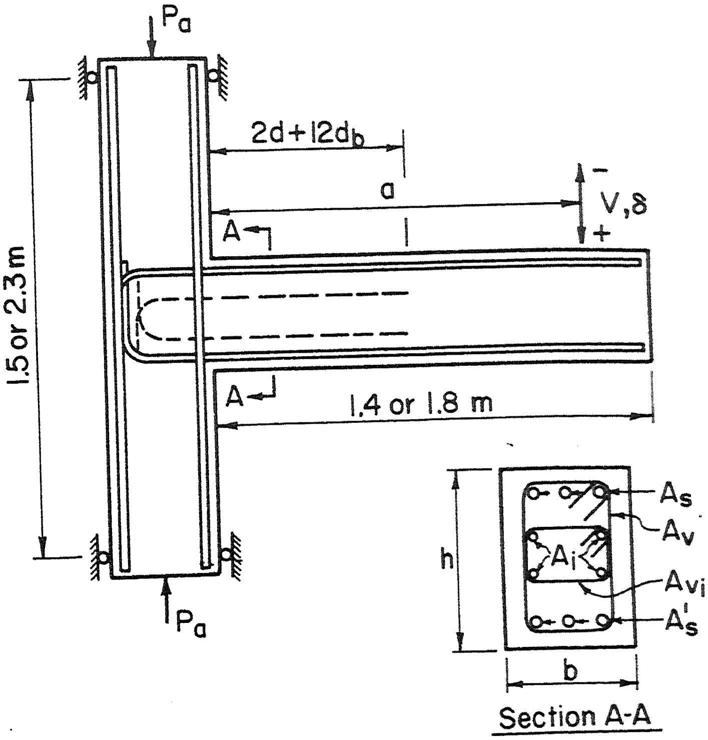

Fig. 1 Specimen Configuration and Dimension Designation

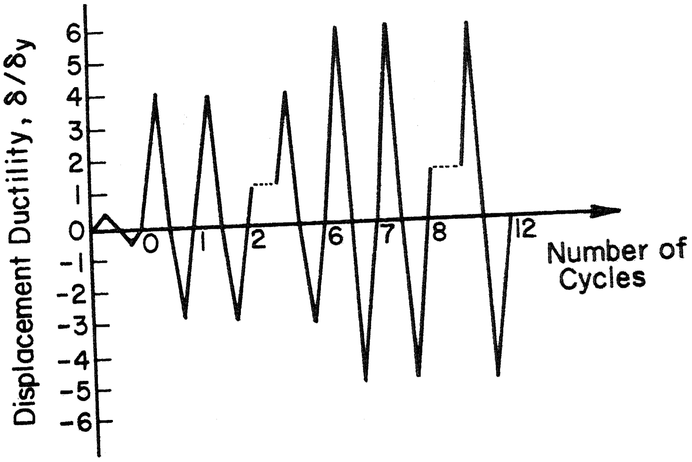

Fig. 2 Typical Loading Schedule

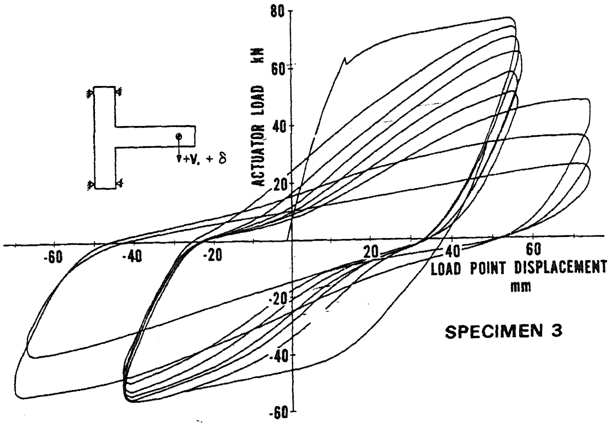

Fig. 3. Load vs Load Point Displacement - Specimen 3

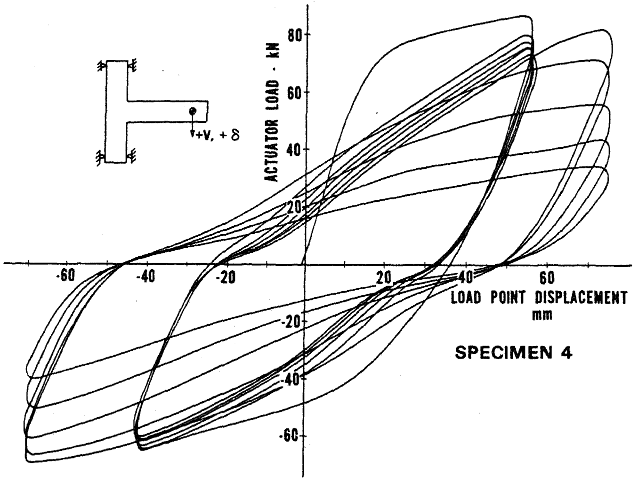

Fig. 4. Load vs Load Point Displacement - Specimen 4