EFFECT OF LOAD HISTORY VARIATION ON CYCLIC RESPONSE OF R/C FLEXURAL MEMBERS

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SUMMARY

An experimental investigation to determine the effect of variations in displacement history on cyclic response of reinforced concrete flexural members is presented. Test results indicated that member behavior and member energy dissipation capacity were functions of the intensity of shear stress and of the magnitude of maximum displacements applied to the members. It was found that cantilever beam specimens of the type tested could endure many more cycles of loading than a typical frame member would be expected to tolerate during a severe earthquake as long as beam tip displacement did not exceed two percent of beam shear span length.

INTRODUCTION

The behavior of R/C members subjected to inelastic cyclic flexure has attracted considerable interest in the past 20 years. However, agreement has not been reached concerning a displacement history representative of what an actual structural member might be forced to endure during a severe earthquake. The loading histories used in the majority of previous test programs have contained maximum displacements of from 5% to 10% of beam shear span length, in effect comparable to structure lateral drifts of similar percentages of story height. In contrast, Applied Technology Council recommendations (Ref. 1) have suggested a lateral displacement of 1.5% of a structure's story height as the maximum allowable design story drift for reinforced concrete frame buildings designed to resist earthquakes.

It is apparent that the displacements applied to structural components during previous research on cyclic inelastic member behavior have been more severe than generally accepted displacement criteria would mandate. As a result, design recommendations which have been based on previous research could be unnecessarily conservative. The first goal of this research was to study the behavior of members subjected to maximum displacements comparable to those of members within a structure displaced to accepted design limits of story drift.

Energy dissipation has been used as a measure of the ability of a member to withstand cyclic inelastic loading (Ref. 2) or as a damage

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indicator. However, it has been noted (Refs. 3,4) that if total energy dissipation capacity of a member were dependent on the displacement sequence applied to that member, any comparison of energies dissipated by different specimens would be meaningful only if the specimens were subjected to similar loadings. The second goal of this investigation was to study the effect of variations of displacement history on the total energy dissipated by members during inelastic cyclic flexure.

EXPERIMENTAL PROGRAM

Eleven doubly reinforced cantilever beam specimens were constructed and tested during this investigation. Specimen configuration is shown in Fig. 1, and critical specimen dimensions and material properties are listed in Table 1. The American Concrete Institute Building Code (318-77), including Appendix A, (Ref. 5) was used as a guide for designing all specimens. Specimens were divided into three groups, designated as low shear, moderate shear, and high shear. The nominal maximum shear stress levels for these groups were intended to be 3, 4.5 and 6 times $\sqrt{f'_c}$ (psi) (or 0.25, 0.38 and 0.50 times $\sqrt{f'_c}$ (MPa)), respectively. The design maximum shear stress for and the actual maximum shear stress applied to each specimen during the first quarter cycle of loading of that specimen are listed in Table 2.

The displacement amplitudes which defined each loading history were expressed in terms of percentages of beam shear span length. Four types of loading were included in this study: loadings which contained uniform maximum displacement amplitudes of either 2% or 4% of beam shear span length, and loading histories which contained both 2% and 4% shear span length maximum displacement amplitudes. These loading histories, designated as Types 1 through 4, are schematically illustrated in Fig. 2.

Testing Procedure

Each specimen was held fixed at its enlarged end block while the beam tip was deflected slowly by a hydraulic actuator. Testing of each specimen was terminated when the specimen had lost essentially all ability to resist displacement, or when the strength of the specimen at its positive maximum deflection had dropped below 50% of the specimen's original yield strength.

TEST RESULTS

Effects of Load History

It is logical to speculate that, during cyclic flexure of a member, an increase of the magnitude of the maximum displacement in each load cycle would cause a reduction of the total number of cycles the member could resist prior to failure. The criterion used to define failure is presented in a subsequent section of this report. The results obtained from these tests indicated that significant changes in member behavior could be linked to the size of applied displacements. This generalization was true for specimens of all shear stress levels, but the effect was most pronounced in high-shear specimens. As shown in Fig. 4, Specimen S3-1 (a high-shear specimen) resisted fifty cycles of loading before failure , while Specimen S3-2, developing a similar maximum shear stress, was able to maintain a stable load-versus-displacement relationship for only four cycles of load before failure was reached. Uniform maximum displacements were applied to each member, with Specimen S3-2 undergoing displacements twice as large as those applied to Specimen S3-1. It should be noted that the load versus displacement curves shown in Fig. 4(a) for Specimen S3-1 include only the traces of load versus displacement behavior for load cycles 1-4, 7, 10, 20, 30, 50, 70 and 100. If all curves had been shown, the trace of a single cycle of loading would have been obscured.

The load-versus-displacement relationships for specimens subjected to Type 3 and Type 4 loading histories (Figs. 4(c), 4(d)) were in some ways similar to that for the specimen subjected to Type 2 loading history, Fig. 4(b). In general, load cycles in which maximum displacements were limited to 2% of shear span length did little damage to the specimen as compared to the load cycles which contained maximum displacements as large as 4% of shear span length. The total number of load cycles at 4% shear span length maximum displacement applied prior to member failure was approximately the same for specimens subjected to Types 2, 3 and 4 loading within all shear levels considered. On this basis, it was concluded that differences in displacement sequence did not cause a significant difference in useful life of these members as long as maximum displacements experienced by the members were comparable.

Effects of Maximum Shear Stress Level

By comparing the total number of load cycles required to produce member failure for each group of specimens, the effects of maximum shear stress level on member behavior can be studied. For a given loading history, low-shear specimens underwent more cycles of load prior to failure than did high-shear specimens. The high-shear specimens showed a higher rate of stiffness decay and larger strength loss at maximum displacements during successive cycles of load than did the low-shear specimens.

Energy Dissipation

To be able to measure in a consistent manner the total energy dissipation capacities of members, a failure criterion was needed. A failure criterion which was based on member strength at a given displacement did not give acceptable results. The fact that many specimens were subjected to displacement histories in which maximum displacements were not equal for all cycles of load made it impossible to arbitrarily consider the specimen to have been failed if it was unable to attain a specified load at maximum displacement during each load cycle. In addition, a general criterion based on physical appearance of the specimen was found to be unreliable. Many specimens retained considerable strength and stiffness even after longitudinal reinforcement had been exposed by spalling of cover concrete. However, if failure of a specimen was defined to have occurred when the member's strength at the largest displacement of its assigned displacement history dropped below 75% of member initial yield strength, the number of load cycles required to develop failure and the total energy dissipated by each specimen could be determined in a consistent manner. Values of energy dissipation determined in this manner are given in Table 2.

In Fig. 3, the actual energy dissipated by each specimen has been plotted versus the maximum shear stress applied to the member during the first quarter-cycle of loading. As shown in this figure, the maximum shear stress affected the members' energy dissipation capacities such that higher shear stresses resulted in a reduction of energy dissipation capacity. However, the effect of variations in maximum shear stress on the members' energy dissipation capacities was small as compared to that of the loading history to which the member was subjected. As shown in Fig. 3, specimens subjected to Type 1 loading history always possessed a larger energy dissipation capacity than did specimens subjected to Types 2, 3 and 4 loading histories. For specimens within each shear group, the difference between energy dissipation capacities was small for specimens subjected to Types 2, 3 and 4 loading histories.

CONCLUSIONS

Based on the results of these tests, the following conclusions can be drawn:

1. The strength and stiffness degradation of reinforced concrete members during repeated reversed inelastic flexure is dependent upon the magnitude of the maximum displacement applied during each cycle and to the maximum shear stress level experienced by the members.

2. The total energy dissipation capacity of a reinforced concrete member depends strongly on the displacement history the member experiences. Estimation of the damage to or comparison of the performance of reinforced concrete members subjected to inelastic reversed loadings must consider the displacement histories which the members have experienced.

3. An increase in maximum gross shear stress in a flexural member causes a reduction in the total number of cycles of load which can be endured prior to an arbitrarily defined failure condition for members subject to any given load history.

4. As long as maximum member flexural displacement is not greater than 2% of a member's shear span length during cyclic reversed loading, the strength degradation taking place in members of the type tested under high maximum nominal shear stresses would not be excessive if the member were detailed in accordance with Appendix A of the American Concrete Institute Building Code (318-77) (Ref. 5). Present tests suggest that such a member

would not be likely to fail or suffer severe stiffness loss during the number of cycles of loading which might conservatively be expected to result from a major earthquake.

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TABLE 1.--Physical Dimensions* and Material Properties** of Specimens

Group (1)	Specimen Number (2)	a, in inches (3)	d, in inches (4)	d', in inches (5)	Number-Bar Designation A_s (6)	A'_s (7)	A_v (8)	f'_c, in pounds per square inch (9)	f_y, in kips per square inch A_s (10)	A'_s (11)	A_v (12)
1	S1-1	39	9.9	2.2	3-No. 6	3-No. 5	No. 2	5900	63.7	72.4	53.4
	S1-2	39	10.1	2.1	3-No. 6	3-No. 5	No. 2	5880	63.7	72.4	53.4
	S1-4	39	9.9	2.1	3-No. 6	3-No. 5	No. 2	4980	62.1	72.4	58.1
2	S2-1	34	9.6	2.3	3-No. 7	3-No. 6	No. 2	5100	59.3	63.7	53.4
	S2-2	34	9.6	2.3	3-No. 7	3-No. 6	No. 2	5390	59.3	63.7	53.4
	S2-3	34	9.7	2.2	3-No. 7	3-No. 6	No. 2	4710	71.8	62.1	58.1
	S2-4	34	9.6	2.2	3-No. 7	3-No. 6	No. 2	4780	59.3	63.7	53.4
3	S3-1	25	9.7	2.5	3-No. 7	3-No. 6	No. 3	4910	59.3	63.7	75.5
	S3-2	25	9.8	2.5	3-No. 7	3-No. 6	No. 3	4970	59.3	63.7	75.5
	S3-3	25	9.6	2.5	3-No. 7	3-No. 6	No. 3	4980	59.3	63.7	75.5
	S3-4	25	9.7	2.6	3-No. 7	3-No. 6	No. 3	5060	59.3	63.7	75.5

*Dimensions shown in Fig. 1.

**Material Properties Averaged for Specimens Cast Simultaneously.

Stirrup spacing for all specimens: 9 @ 2.5 in., thereafter at 5 in. spacing to end of beam.

Specimen S1-3 damaged irreparably in a pilot test--could not be tested in manner required.

Note: 1 in. = 25.4 mm.
1000 psi = 1 ksi = 6.89 MPa.

TABLE 2.—Selected Testing Parameters and Test Results

Specimen Number (1)	Load History (2)	Design* Max. Shear Stress (3)	Actual* Max. Shear Stress (4)	a/d (5)	Total No. of Cycles** (6)	Modified Work Index*** (7)	Total Energy Dissipation, in inch-kips (8)
S1-1	1	3.0	3.3	3.9	110	169	590
S1-2	2	3.0	3.6	3.9	13	40	343
S1-4	4	3.0	3.5	3.9	13	31	248
S2-1	1	4.5	5.1	3.5	60	88	360
S2-2	2	4.5	5.2	3.5	4	11	160
S2-3	3	4.5	6.0	3.5	7	16	171
S2-4	4	4.5	5.6	3.5	5	13	151
S3-1	1	6.0	7.1	2.6	50	78	320
S3-2	2	6.0	7.3	2.6	4	11	155
S3-3	3	6.0	7.0	2.6	8	17	196
S3-4	4	6.0	7.4	2.6	6	14	178

*Maximum shear stress measured at maximum positive displacement in first load cycle; as a multiple of $bd\sqrt{f'_c}$, psi units.

**Failure defined to have occurred in the cycle in which restoring force at maximum positive displacement was less than 75% of original yield force.

***Calculation of modified work index based on Gosain, et al. (Ref. 2).

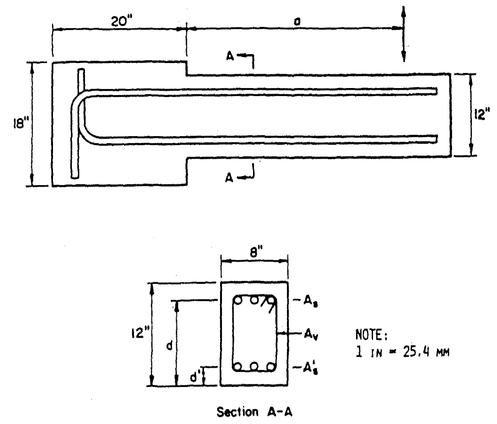


Fig. 1 Specimen Configuration

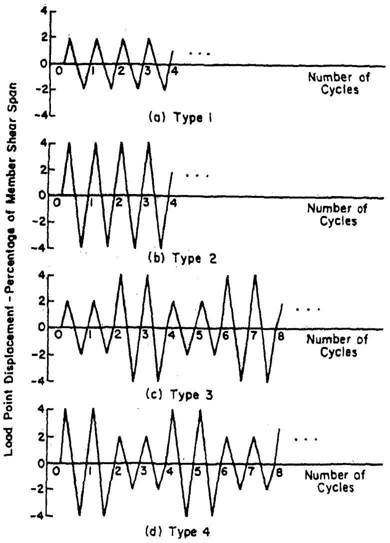


Fig. 2 Displacement Histories

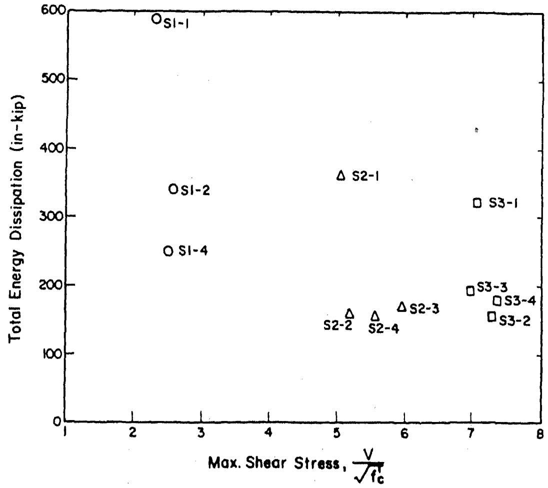
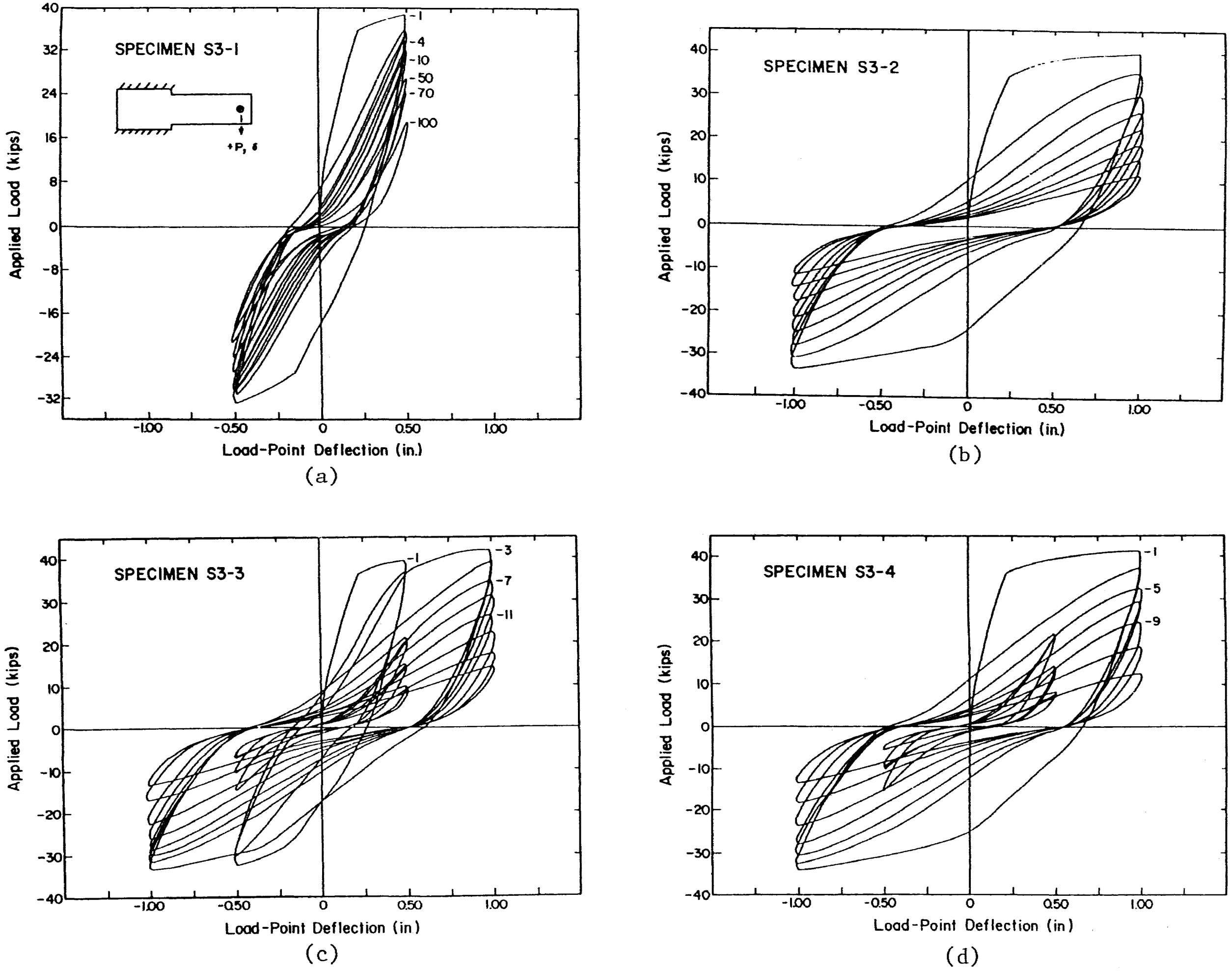


Fig. 3 Total Energy Dissipation versus Shear Stress



(a) (b)

(c) (d)

Fig. 4 Load versus Load-Point Deflection for Four Specimens