RATE OF LOADING EFFECTS ON UNCRACKED AND REPAIRED REINFORCED CONCRETE MEMBERS

by

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SYNOPSIS

The effects of high loading rates on the behavior of reinforced concrete structures and the effectiveness of the epoxy-injection technique of repairing cracks in such structures have been studied through tests on simply supported, doubly reinforced, concrete beams. High loading rates on regions subjected mainly to flexure were found to increase the yield strength on the first excursion beyond yield. The stiffness was essentially restored in the repaired beams but the mode of failure of the repaired beams differed from that of the non-repaired beams.

INTRODUCTION

The work described herein is part of a general analytical and experimental program of research being conducted at the University of California, Berkeley. Its purpose is to investigate the effects of generalized excitations, such as those expected from earthquake ground motions, on reinforced concrete structures(1). This paper deals with two problems: (i) the effects of strain rates on the behavior of concrete structures, and (ii) the repairability of damaged reinforced concrete structures. It has been recognized for many years that the behavior of materials under dynamic loading differs from their behavior under quasi-static loading(2). The quasi-static stress-strain relationship is altered by increasing the rate of strain, and this may modify the mode of failure with increased probability of brittle failure. Furthermore, dynamic loadings may reverse sense which introduces the problem of low cycle fatigue. In spite of these effects, most seismic resistant structural designs are based on results obtained from quasi-static tests. The importance of designing structures to have high ductility to withstand earthquake loadings in now widely recognized(2). One of the main factors controlling the selection of permissible ductility factors in seismic design is the degree of damage that can be tolerated in a severe earthquake. The larger the ductility designed into the structure, the greater the damage it can suffer in an earthquake without collapsing. Methods are now being developed to repair earthquake damaged reinforced concrete structures. One method proven effective and economical in the repair of damaged highway bridges, warehouse floor slabs, etc. is the injection of epoxy resins into cracks. This method is now being employed for the repair of earthquake damaged structures, but there is little evidence to show how such structures will behave in subsequent earthquakes.

Six beams were tested as part of the experimental phase of the research project. Two beams were tested to evaluate the experimental techniques developed for testing at high loading rates. The data for the two problems under study were obtained on two pairs of beams loaded at their third

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points to induce a zone of constant bending moment. Both low and high loading rates were applied to each specimen but the order was interchanged for each specimen of a pair. The first pair were loaded monotonically up to a maximum displacement of about ten times the yield displacement: one at high displacement velocity and the other quasi-statically. Each beam was subsequently cyclically loaded (including reversal of displacements) until failure. The second pair of beams were initially subjected to a history of deformations which just exceeded first yielding. These two specimens were then repaired by injecting all cracks wider than 0.002 in. with epoxy resins. These repaired beams were then tested by repeating their initial loading history and then by incrementally increasing the magnitude of displacements until failure. The specimens, experimental technique, test program, and results are described below. The significance of the results is then evaluated.

TEST SPECIMENS AND MATERIAL CHARACTERISTICS

The specimen selected for this investigation was similar to that used in previous quasi-static tests, described in Reference 1 and shown in Fig. 1. Two beams were cast at a time from the same batch of concrete in order to obtain pairs of beams with similar concrete properties. The reinforcement consisted of deformed bars of intermediate grade steel conforming to ASTM designation A15. Stress-strain relationships were determined under tensile loads for samples of the longitudinal reinforcing bars at average strain rates of 50, 5,000, and 50,000 μin/in/sec. The standard main mechanical characteristics, determined at the slowest strain rate, are shown in Fig. 2(a). The main effect of higher strain rates was to increase the yield strength. The increases in yield strengths, above the quasi-static ones, were 16% and 28% for average strain rates of 5,000 and 50,000 μin/in/sec, respectively. As shown in Fig. 2(b), for a given strain rate, after the first excursion beyond yielding, the percentage increase in strength decreases for subsequent loading cycles even if these are in the plastic plateau range. The concrete mix was designed to achieve an ultimate strength of 4000 psi in 28 days. The properties of the concrete at the time each beam was tested were determined from the compressive stress-strain relationship for 12 in. control cylinders cast from the same batch of concrete as the beam. These relationships under quasi-static loading are shown in Fig. 3(a), where the main mechanical characteristics of the concrete are also tabulated. As shown in Fig. 3(b), the main effects of high strain rates were an increase in stiffness and compressive strength.

LOADING APPARATUS, DATA ACQUISITION SYSTEM, AND DATA REDUCTION

LOADING APPARATUS(3): The loading apparatus consists of two basic parts: the test rig and the loading system. Photo 1 illustrates the arrangement of these two basic parts. The test rig consists of two heavy columns which are attached to a structural test floor by high strength prestressing rods. Each column supports a yoke into which one end of a beam is rigidly clamped. The location in space of one yoke is fixed by its column, while the other yoke is permitted to move freely in the longitudinal direction of the test beam by a hinged joint in its support column close to the floor. Thus the rig simulates simply supported boundary conditions for a test beam. The loading system consists of two independent hydraulic actuators operating in parallel. Each actuator is controlled by a closed-loop feedback system in which the command signal may represent force or displacement. In the tests, a signal representing displacement was fed simultaneously to both actuators from a low frequency function generator.

DATA ACQUISITION AND REDUCTION: The behavior of the beams during the tests was monitored by a number of different types of transducers. After amplification, the signals from the transducers were fed to ultra-violet light type recorders which provided a continuous record of the signals during a test. Load cells, incorporated in the actuators, measured the forces being applied at the one-third span points of the beams. Linear variable differential transformers (LVDT's), also incorporated in the hydraulic actuators, measured the displacements at the one-third span points, and another LVDT measured the displacement of the center of the beams. The curvatures along the central portions of the beams were determined from the relative displacements at the top and bottom of vertical reference frames attached to the beam at 6 in. centers. The relative displacements were measured by means of specially designed clip gages attached to the reference frames as shown in Photo 2(1). Special transducers were also used to monitor the strain over a 6 in. gage length of two longitudinal reinforcing bars and to measure the width of one of the main flexural cracks at the center of the beam(1). The data were read from the recorder charts and placed on punched cards by a semi-automatic technique. Computer programs were written to read the data from the punched cards, analyse and reduce them for presentation in appropriate graphical form.

TEST PROGRAMS AND RESULTS

SELECTION OF TEST PROGRAM: The loading program was selected specifically to evaluate strain rate effects, rather than to simulate response to any real dynamic excitation. Different strain rates were applied by moving the actuators with different displacement velocities. Two main velocities were used: one was the highest permitted by the system, 10 in/sec; and the other was to achieve a quasi-static rate, 0.1 in/sec. A pair of beams were subjected to similar displacement histories but with rates interchanged. Each beam was forced downward to a specified displacement at a constant velocity for several cycles until the behavior stabilized. These cycles were then repeated at a different velocity, and finally the original displacement rate was again imposed. To investigate displacement reversal, several cycles with sinusoidal displacement functions were applied. Typical displacement histories are shown in Fig. 4.

BEAMS 1 AND 2: These beams were loaded monotonically to a maximum centerline displacement of about 5 in. which corresponded to a displacement ductility of 12.8 for beam 1. Initially, beam 1 was tested quasi-statically and beam 2 at a high rate. The force-displacement relationships during the first significant loading cycle for these beams are compared in Fig. 5(a), and the complete history of beam 1 is shown in Fig. 5(b).

BEAMS 3 AND 4: As shown in Fig. 6, the significant testing on beam 3 started with high velocity cycling and on beam 4, quasi-statically. In order that these specimens could be repaired, displacements were limited to ± 0.75 in., i.e., just enough to induce some yielding in the main reinforcement. The force displacement relationships for these beams are compared in Fig. 6.

DAMAGE REPAIR OF BEAMS 3 AND 4: Cracks wider than 0.005 in. developed in the central third of these beams. These cracks were repaired by the injection of epoxy resins. The cracks were sealed except for ports at the beam surface with a fast drying epoxy. Epoxy resins were forced under pressure into the entry ports on one side of the beam until flow was detected through ports on the other side (Photo 3). After the epoxy cured, the temporary seal was removed. The repaired beams were designated as beams 3R and 4R.

TEST PROGRAM FOR BEAMS 3R AND 4R: These beams were initially subjected to the same displacement time histories as beams 3 and 4. Then they were subjected to further loading cycles at displacement amplitudes of 1.5, 3.0, and 4.5 in. (Fig. 4). Cycles at high velocity and quasi-static rates were applied at each of these amplitude levels. Force-displacement relationships are shown in Figs. 7 and 8.

OVERALL BEHAVIOR OF EACH SPECIMEN AND ITS MODE OF FAILURE: Beams 1 and 2: The top concrete cover over a large portion of the middle third started to spall during the first downward deflection of 5 in. (Photo 2). This spalling progressed with each cycle and the top reinforcement buckled by the fourth major cycle. After the first cycle with deformation reversal, the bottom concrete cover of beam 1 spalled, and several cracks remained open over the beam's full depth. During the third cycle with deformation reversal (Cycle 10), one of the top bars of beam 2 fractured (Photo 4). By Cycle 16, the damage to beam 1 was so severe that the test was halted.

Beams 3R and 4R: The damage resulting from the tests at 0.75 in. displacement was similar to the damage of beams 3 and 4. Cracks in the repaired beams, which are the lighter lines in Photo 5, did not reform along the original repaired cracks. As the deformation amplitude increased, the damage pattern altered considerably. Significant diagonal tension cracks developed just outside the middle third of the beams which resulted in their shear failure (Photo 6). In marked contrast to beams 1 and 2, no spalling of the concrete cover was observed on beams 3R and 4R.

EVALUATION OF TEST RESULTS[IV]

PERFORMANCE OF SYSTEM: The experimental facilities performed satisfactorily. The forces developed by the actuators exhibited transients resulting in significant differences in actuator force amplitudes whenever there was any sharp change in stiffness of the beams (as in the case of first yielding). Thus it is advisable that further dynamic tests use only one actuator, necessitating in this case a force divider(1). The instrumentation supplied the required data. However, the dynamic nature of the tests required care in the selection of scale sensitivities and considerable effort in data reduction.

STRAIN RATE EFFECTS: To evaluate these effects it is necessary to recognize that the results obtained with a displacement rate of 10 in/sec corresponds to a strain rate of about 40,000 μin/in/sec. Results obtained at different velocities have been evaluated regarding their effects on the following main mechanical characteristics of structural behavior.

[IV] Reference 4 gives a detailed evaluation of the results.

Stiffness: Because of the increased stiffness of concrete at high strain rates (Fig. 3), the dynamic secant stiffness at first yielding was typically about 10% higher than the quasi-static stiffness (Figs. 5-7). Since an increase of 10% in the stiffness of a structure will lead to a decrease of less than 5% in its period, it can be concluded that the strain rate will not significantly affect the initial linear seismic response of buildings.

Strength: The strength at the following limit states is of relevance in reinforced concrete members: CRACKING: It was difficult to detect first cracking. However, from records of beams 3 and 4 (Fig. 6), it appears that there was an increase of about 25% in the cracking strength. YIELDING: These results are summarized in Table 1. The yielding strength at high velocities was about 22% higher than the quasi-static strength. Furthermore, the predicted quasi-static yield strengths are about 10% less than the measured strengths, which is in accordance with the so-called yielding hyperstrength generally observed in flexural tests. Beams 3R and 4R did not exhibit a definite upper yield point (Fig. 7); however, they did develop maximum strengths slightly higher than those corresponding to the lower yielding strengths of beams 3 and 4. Beam 3R had 13% higher yielding strength than the quasi-statically loaded beam 4R. During the first reversal of deformations, the yield strengths were also increased by the strain rate. MAXIMUM AND ULTIMATE STRENGTH: The effects of loading rate diminished with increasing displacement amplitudes (Figs. 5-7). This is in accordance with tests on reinforcing bars (Fig. 2). Thus these strengths were not affected by high strain rates.

Mode of Failure: No effect of strain rate was observed. Thus it would appear that for ductile reinforced concrete members subjected primarily to flexure, seismic strain rates will not affect the failure mode. In contrast the loading history did have a pronounced effect.

Ductility: Because the yield deformations were increased only slightly by high strain rates and all specimens were able to sustain large inelastic deformations, there was little effect of these high rates on the resulting strain, average curvature, rotation, and deflection ductility factors.

Energy Absorption and Dissipation: The rate of loading influenced only significantly the energy absorbed during the first excursion to a displacement amplitude at or just beyond first yielding. Since the effect of rate of loading on strength diminished as the amplitude of the displacement increased beyond yielding, the less significant the strain rates became regarding these energies. Consequently, beam 1 dissipated 5% more energy during the first yielding cycle than beam 2, while beam 3 dissipated 20% more than beam 4 (Figs. 5 and 6).

EFFECTIVENESS OF THE EPOXY-INJECTION REPAIR TECHNIQUE: Stiffness: The initial stiffness of the repaired beams was somewhat lowered because all cracking was not repaired. Load-displacement curves for these beams did not exhibit a definite transition at cracking or yielding (Fig. 7). It is believed that the bond between the reinforcing steel and the concrete was not fully repaired; after cracking, the response of the repaired beams was similar to the original beams subjected to their entire previous loadings.

Strength: While these beams did not have an upper yield point, they did develop maximum strengths slightly higher than the lower yield points of the original beams (Fig. 7). MAXIMUM AND ULTIMATE STRENGTHS: Beams 1, 2, 3R, and 4R were able to develop nearly the same maximum strength. Envelopes of the load-displacement curves for beams 3R and 2 are compared in Fig. 8. The only significant difference between these envelopes is that while beam 2 reaches its maximum positive strength prior to the ultimate deformation, beam 3R does not. This emphasizes the importance of loading history for reinforced concrete members(2).

Mode of Failure: The most significant differences between the behavior of repaired and non-repaired beams were the different modes of failure. While beams 1 and 2 failed due to the buckling of the main reinforcement, no spalling of concrete was observed in beams 3R and 4R. This particular difference was not a direct consequence of the repairing technique, but the result of the different load-displacement histories. Beams 3R and 4R failed in shear where damage accumulated in the unrepaired cracks outside the region of constant moment.

Energy Absorption and Dissipation: Fig. 8 indicates that the repaired beam 3R had a slightly smaller energy absorption capacity than beam 2. This was a consequence of the combined effects of repair and loading history. As a consequence of the different loading histories, the total energy dissipated by beams 3R and 4R was considerably larger than for beams 1 and 2.

CONCLUSIONS AND RECOMMENDATIONS

EFFECTS OF STRAIN RATE: The principal effect of strain rate expected to develop during seismic response of relatively rigid structures is the increase in moment capacity at the first yielding of the reinforcement. Although it might be conservative to neglect this for members under pure flexure, it might not be so for flexural members under high shear and/or axial forces. This could trigger a brittle shear failure during an earthquake. Thus the effects of the highest expected seismic strain rate on flexural members subjected to high shear and/or axial forces should be investigated. Meanwhile, shear reinforcement should be designed for shear computed on the basis of moment capacities which consider the increase due to the highest expected strain rate. The test results emphasize also the need to study the effects of loading history on the performance of reinforced concrete elements.

EFFECTIVENESS OF EPOXY-INJECTION TECHNIQUE: This method was effective in restoring the overall stiffness of the members at working load level. Small cracks and the "bond" between reinforcement and concrete could not be fully repaired. These could lead to cumulative damage, and, therefore, to premature failure. This repairing technique should be thoroughly investigated for members whose critical regions are subjected to high shear and also regions where reinforcement anchorage could control response. Furthermore, tests should be conducted to determine the maximum earthquake damage that should be repaired by this technique.

ACKNOWLEDGEMENT

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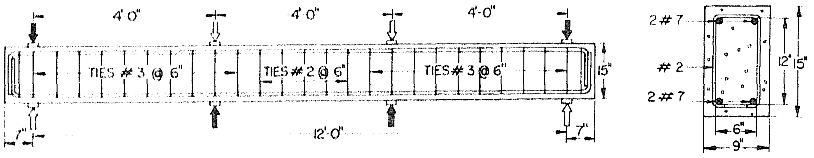
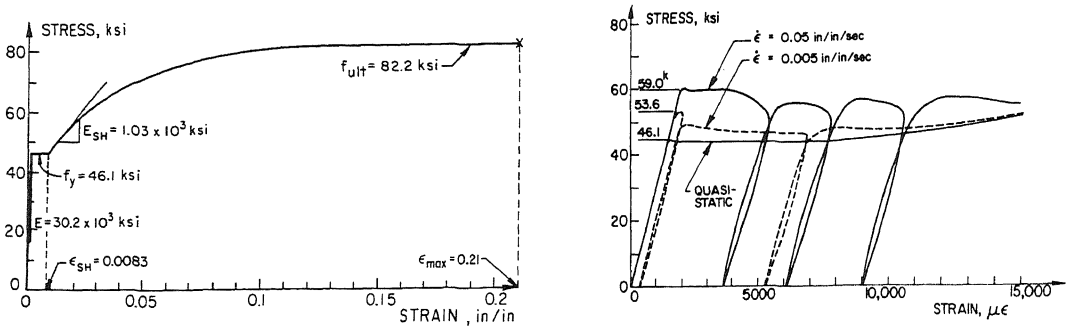
FIGURES, TABLE AND PHOTOS



LOADING AND REINFORCEMENT DETAILS

CROSS SECTION

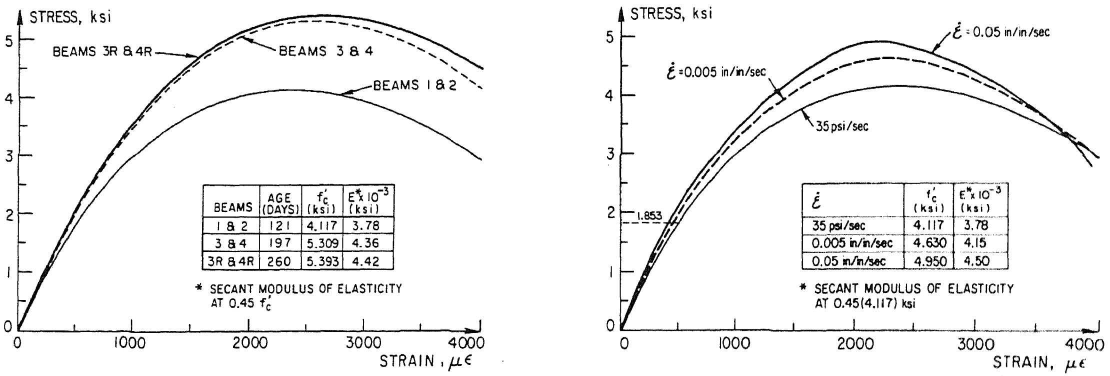
FIG. 1 DETAILS OF TEST SPECIMEN



(a.) QUASI-STATIC

(b.) EFFECT OF RATE OF STRAIN, $\dot{\epsilon}$

FIG. 2 MECHANICAL CHARACTERISTICS OF MAIN REINFORCING STEEL



BEAMS	AGE (DAYS)	f'_c (ksi)	$E^* \times 10^{-3}$ (ksi)
1 & 2	121	4.117	3.78
3 & 4	197	5.309	4.36
3R & 4R	260	5.393	4.42

* SECANT MODULUS OF ELASTICITY AT 0.45 f'_c

$\dot{\epsilon}$	f'_c (ksi)	$E^* \times 10^{-3}$ (ksi)
35 psi/sec	4.117	3.78
0.005 in/in/sec	4.630	4.15
0.05 in/in/sec	4.950	4.50

* SECANT MODULUS OF ELASTICITY AT 0.45(4.117) ksi

(a.) QUASI-STATIC, 35 PSI/SEC

(b.) EFFECT OF RATE OF STRAIN, $\dot{\epsilon}$

FIG. 3 MECHANICAL CHARACTERISTICS OF CONCRETE

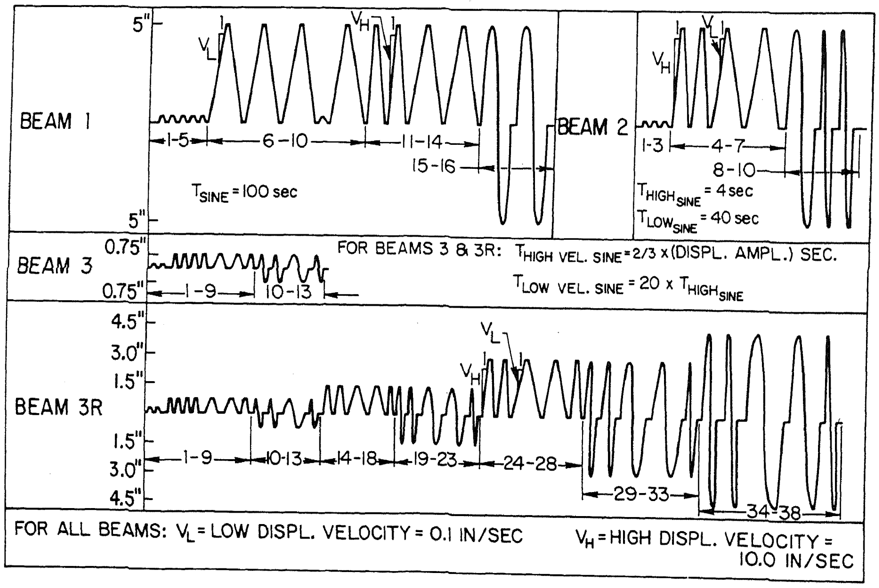


FIG. 4 DISPLACEMENT HISTORIES

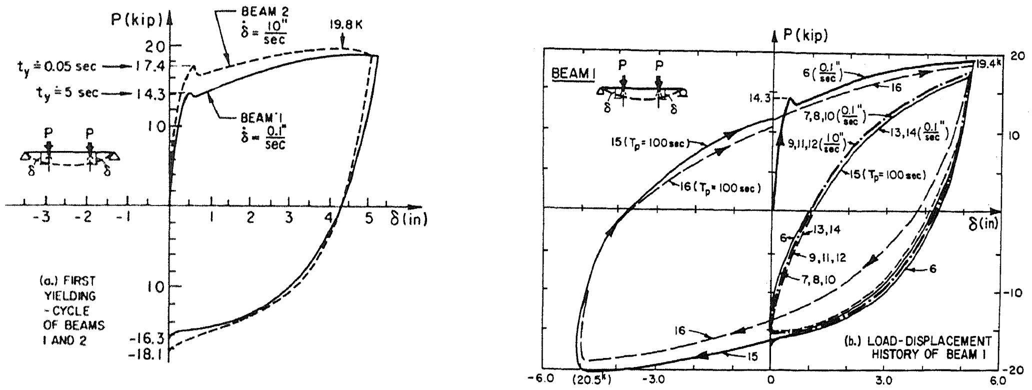


FIG. 5 LOAD-DISPLACEMENT RELATIONSHIPS OF BEAMS 1 AND 2

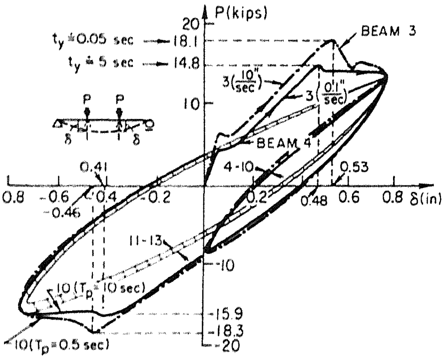


FIG. 6 LOAD-DISPLACEMENT HISTORIES OF BEAMS 3 AND 4

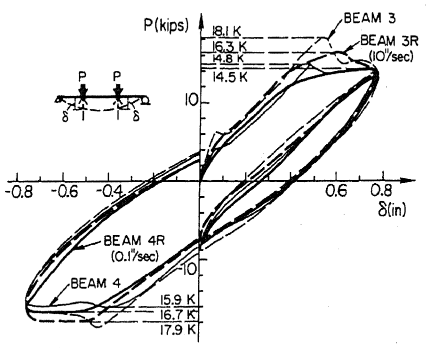


FIG. 7 LOAD-DISPLACEMENT CURVES OF BEAMS 3R, 4R, 3 AND 4

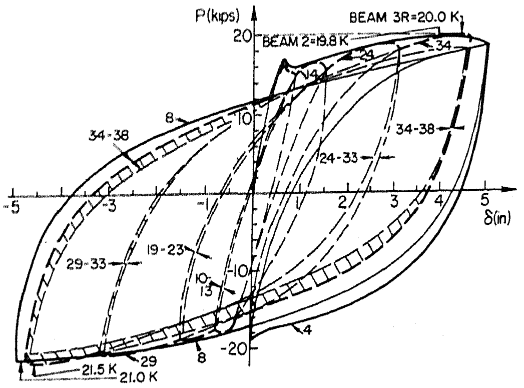


FIG. 8 LOAD-DISPLACEMENT HISTORY OF BEAM 3R AND COMPARISON OF ITS ENVELOPE WITH THAT OF BEAM 2

BEAMS	1	2	3 3 R	4 4 R
DISPLACEMENT RATE (IN/SEC)	0.1	10	10	0.1
UPPER YIELD FORCE (K)	14.33	17.36	18.06	14.80
LOWER YIELD FORCE (K)	13.42	15.93	14.8 16.3	14.0 14.5
M_y (PREDICTED)*, (K-IN)	642.2	642.2	649.8	649.8
YIELD FORCE*, (K)	12.25	12.25	12.42	12.42

* Based on experimental pseudo-static stress strain relationship of materials.

TABLE 1 YIELDING STRENGTHS

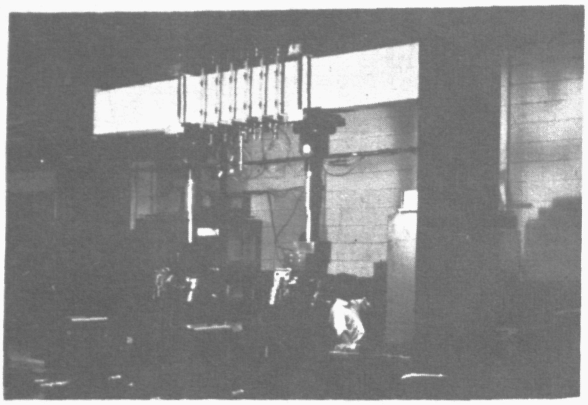


PHOTO 1 TEST RIG

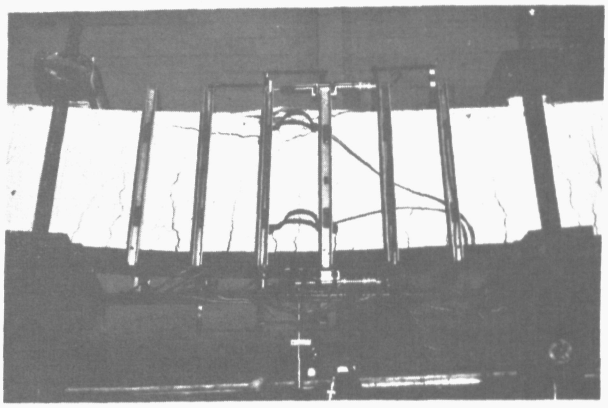


PHOTO 2 INSTRUMENTATION

PHOTO 3 REPAIR OF BEAM

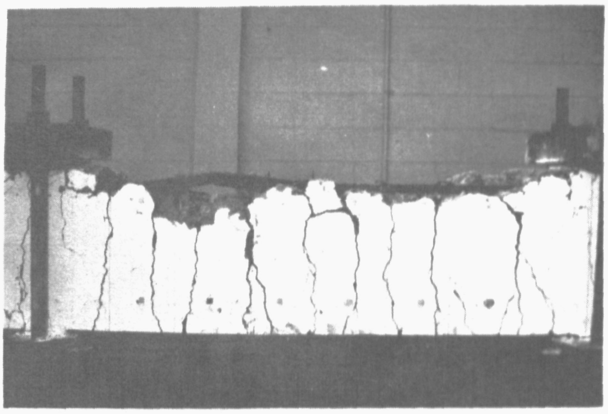


PHOTO 4 BEAM 2 AFTER FAILURE

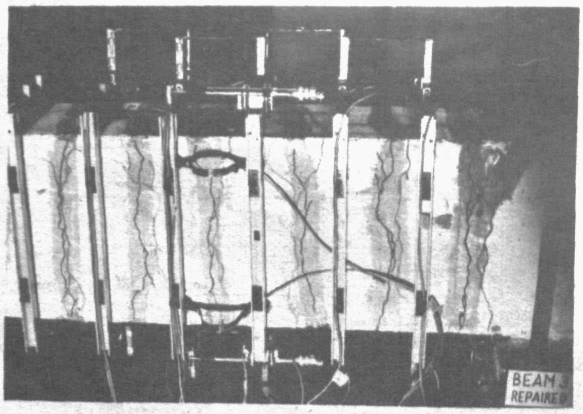


PHOTO 5 CRACK PATTERN, BEAM 3 AND 3R

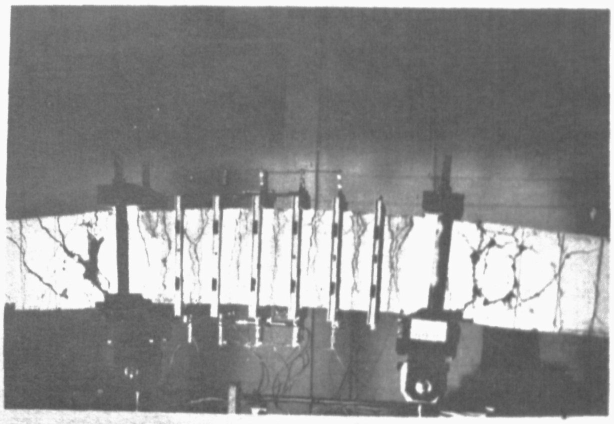


PHOTO 6 FAILURE MODE, BEAM 3R