DYNAMIC LOADING EFFECTS ON THE STRUCTURAL PERFORMANCE OF CONCRETE AND STEEL MATERIALS AND BEAMS

by

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SUMMARY

Effects of a strain rate on the fundamental properties of concrete and steel materials are examined experimentally in the first half of the paper. In the latter half, effects of a curvature rate on the elastic-plastic behavior of steel beams and reinforced concrete beams subjected to static and dynamic bending are discussed on the basis of the experimantal and theoretical investigations. It is recognized that compressive strength of concrete and yield stress of steel increase with increasing strain rate and consequently the moment bearing capacity of beams under dynamic loading increases comparing with that under static loading.

INTRODUCTION

A number of quasi-static experiments under monotonic and cyclic loadings have been done in earthquake countries to investigate the behavior of structures subjected to earthquake excitation. As a fruit of these experimental studies, many valuable informations on load carrying capacity, deformation capacity, hysteretic characteristics and so on, were obtained. However, since structures are imposed considerably high strain rates during an earthquake, the effects of a strain rate on the behavior of structures should be investigated and some informations from quasi-static tests might be improved partly. From this point of view, in the first half of this paper, stress-strain relationships of concrete and steel materials are examined experimentally under high strain rates which would be imposed to structures due to an earthquake, and in the latter half, effects of a curvature rate on the elastic-plastic behavior of steel beams and reinforced concrete beams subjected to quasi-static and dynamic monotonic bending are discussed on the basis of the experimental and analytical methods.

DYNAMIC PROPERTIES OF CONCRETE AND REINFORCING STEEL BARS

Properties of Concrete   Forty five cylindrical specimens with 50 mm diameter and 100 mm height were tested. Concrete was designed to have a compressive strength of 255 kg/cm^2 after 28 days. A mix proportion of concrete and specific gravities of materials are listed in Table 1. Age of specimens at test was 72-74 days. A testing machine controlled by a electro-hydraulic servo-system was used. A closed-loop feedback system was used to control the force, actuator ram stroke or displacement of specimens. Four electrical resistance strain gages with 60 mm gage lengths were mounted at the midheight of a specimen. Relative displacement between upper and lower surfaces of the specimen was measured by two linear variable differential transformers

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which were set symmetrically about the longitudinal axis of a specimen as shown in Fig. 1. A strain rate was controlled by a feedback system to keep the prescribed value through the whole process of loading. The strain rate in dynamic loading was set in the range between 0.005 sec^{-1} and 0.10 sec^{-1}, taking natural periods of actural reinforced concrete structures into consideration. Two types of loading were planned. Thirty specimens were tested under monotonic compressive loading, and every five specimens of them were subjected to one of six prescribed values of a strain rate. Fifteen specimens were tested under repeated compressive loading at one of four prescribed values of that, and loading was controlled by amplitudes of load or displacement. Load signal from the actuator and signals from differential transformers and strain gages were recorded by a data recorder and were output to a pen recorder or an X-Y recorder.

The results of monotonic loading tests are listed in Table 2. The relationships between stress σ and average strain ε measured from four strain gages are summarized for every strain rate in Fig. 2. Fig. 3 shows a plot of maximum stress versus the logarithm of the strain rate calculated from a rate of the displacement measured by the differential transformers. The marks ✦ in the figure show the average values of the test results for each strain rate. The broken line is the regression line by the method of least squares for the test results. The maximum stress becomes larger as a strain rate increases. It is observed that the average maximum stress is 14 % higher at the strain rate of 0.005 sec^{-1} and 24 % higher at that of 0.05 sec^{-1} than at the quasi-static rate (0.00002 sec^{-1}). Scattering of stress level might be larger with increasing strain rate. However, when the stress-strain diagram is non-dimensionalized by the maximum stress, F_c, in stress and the strain at the maximum stress, ε_c, in strain for each specimen, the normalized stress-strain curves are almost identical in their geometrical shapes, as shown in Fig. 4. The non-dimensionalized curves have almost same configuration in spite of the difference of a strain rate. The average stress-strain relationships for every strain rate are shown in Fig. 5. It is observed from this figure that the maximum stress and the initial tangent modulus vary due to the change of a strain rate but that a strain rate has no effect on the average strain at the maximum stress. Figs. 6 and 7 show plots of the initial tangent modulus and the strain at the maximum stress versus the logarithm of the strain rate, respectively. There was no significant difference in the manner of failure of the concrete cylinders in dynamic and quasi-static tests.

The results of repeated loading tests are shown in Table 3. Fig. 8 shows stress-strain relationships under repeated loading and the broken curves in the figure are average stress-strain relationships under monotonic loading at the identical strain rate. In case of repeated loading the maximum stress becomes larger with increasing strain rate as well as in case of monotonic loading.

Dynamic splitting tests of twenty concrete cylinder specimens were also made. Fig. 9 is a plot of the tensile strength versus the stress rate. It is recognized that the tensile strength of concrete increases under dynamic loading as well as in case of compressive loading.

Properties of Steel Reinforcing Bars   Sixteen of steel bar specimens were made of SR 24 round bars with 13 mm diameter, and the other sixteen

Table 1 Mix Proportions for Concrete Cylinders

	Normal Portland Cement	Sand, smaller than 1.2 mm in sieve size	Gravel, size from 5 mm to 10 mm	Water-Cement Ratio, by weight	Slump
Specific Gravity	3.15	2.53	2.56	64 %	21 cm
Mix Proportions by weight	1	2.45	2.75		

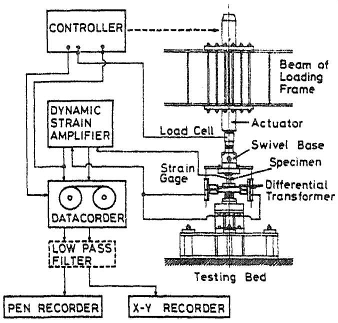


Fig. 1 Testing System

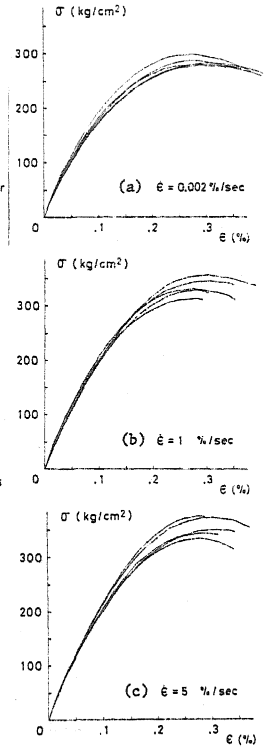


Fig. 2 Stress-Strain Curves

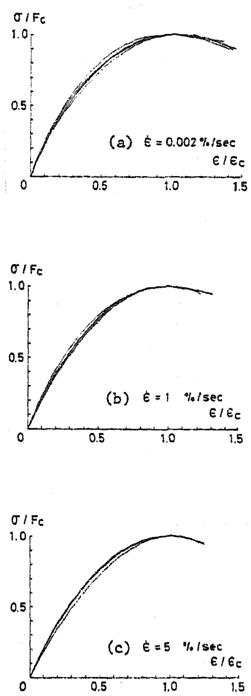


Fig. 4 Normalized Stress-Strain Curves

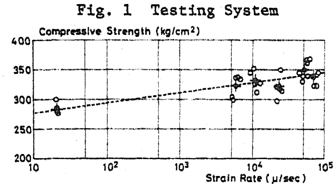


Fig. 3 Maximum Stress

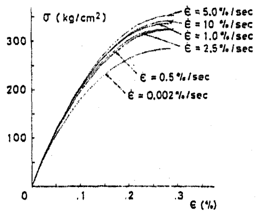


Fig. 5 Average Curves

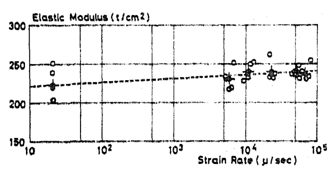


Fig. 6 Elastic Modulus

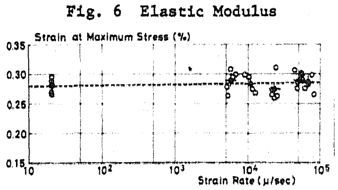
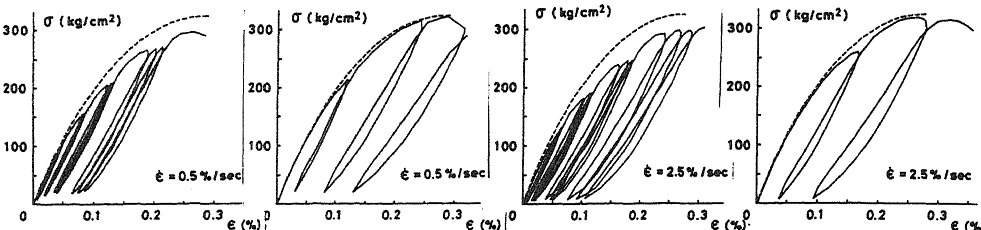


Fig. 7 Strain at Maximum Stress

Table 2 Summary of Test Results of Concrete under Monotonic Loading

Nominal Strain Rate (%/sec)	Strain Rate (%/sec)		Sectional Area (cm²)	Maximum Stress (kg/cm²)	Strain at Maximum Stress (%)	Initial Tangent Modumus (t/cm²)	
	Differential Transformer	Strain Gage					
0.002	0.00207 0.00003	0.00175 0.00007	19.66 0.06	283 7	0.280 0.013	224 21	m. v.* s. d.
0.5	0.587 0.063	0.503 0.047	19.71 0.08	322 19	0.289 0.018	231 14	m. v. s. d.
1.0	1.10 0.13	1.21 0.11	19.79 0.10	332 16	0.284 0.013	240 10	m. v. s. d.
2.5	2.32 0.17	2.46 0.26	19.79 0.06	320 19	0.274 0.021	239 13	m. v. s. d.
5.0	5.16 0.69	4.81 0.56	19.73 0.05	350 17	0.289 0.014	241 4	m. v. s. d.
10.0	6.87 1.13	7.29 0.91	19.74 0.06	338 16	0.286 0.014	237 10	m. v. s. d.

* m. v. : mean value
s. d. : standard deviation



(a) C-R3 (b) C-R4 (c) C-R5 (d) C-R6

Fig. 8 Stress-Strain Curves of Concrete under Repeated Loading

Table 3 Test Results of Concrete under Repeated Loading

Nominal Strain Rate (%/sec)	Specimen Name	Strain Rate (%/sec)		Sectional Area (cm^2)	Maximum Stress (kg/cm^2)	Strain at Maximum Stress (%)
		Differential Transformer	Strain Gage			
0.005	C-R1	0.00497	0.00243	19.69	305	0.267
	C-R2	0.00503	0.00268	19.61	293	0.270
0.5	C-R3	0.480	0.223	19.62	295	0.263
	C-R4	0.484	0.296	19.81	319	0.285
2.5	C-R5	2.18	1.06	19.78	297	0.304
	C-R6	2.24	1.31	19.83	315	0.262
5.0	C-R7	4.27	2.21	19.80	321	0.294

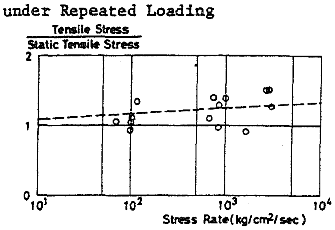


Fig. 9 Tensile Strength

were made of SD 30 deformed bars with 13 mm diameter. Dimensions of a specimen are shown in Fig. 10. At both ends of the bar, steel plates with 15 mm thickness were welded to be held by a testing machine. After welding specimens were annealed. Deformation of a specimen was measured by two differential transformers attached to the end plates. Strain gages with 5 mm gage length were used for round bar specimens and those with 2 mm gage length were used for deformed bar specimens. Four values of strain rates were selected for both monotonic and repeated tensile loadings.

The test results of round bars and deformed bars are given in Tables 4 and 5, respectively. Stress-strain relationships are shown in Fig. 11, grouping the specimens in accordance with a strain rate. In Fig. 12, the stress-strain relationships near yield plateau range at the elevated strain rates in monotonic loading tests are compared with each other. It is recognized that envelopes of stress-strain diagrams under repeated loading almost coincide with curves under monotonic loading. Figs. 13, 14 and 15 show plots of upper yield stresses, lower yield stresses and ultimate strengths of round bars versus the strain rate, respectively. The marks ✦ show the average values of stress in the identical group of a strain rate. The upper and lower yield stresses increase with increasing strain rate. The average lower yield stress of round bars is 8 % higher at the strain rate of 0.005 sec^{-1} and 16 % higher at 0.10 sec^{-1} than at the quasi-static rate (0.00005 sec^{-1}). The average lower yield stress of deformed bars is 7 % higher at the rate of 0.005 sec^{-1} and 18 % higher at 0.10 sec^{-1} than at the quasi-static rate. The increase in upper yield stresses is almost the same as that in lower yield stresses. In strain-hardening region, the increase in stress due to a strain rate is not so large as the increase in yield stress. The ultimate strength in dynamic tests increases at most by 3 % in round bars and 5 % in deformed bars, comparing with that in quasi-static tests. A strain rate has no effect on elastic modulus as shown in Fig. 16. In Fig. 17, it is shown that strain at the beginning of strain-hardening increases depending on the increase of yield stress with increas-

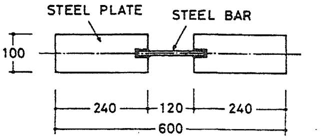


Fig. 10 Test Specimen of Steel Bar

Table 4 Summary of Test Results of Round Bars

Nominal Strain Rate (%/sec)	Strain Rate (%/sec)	Sectional Area (cm^2)	Elastic Modulus (t/cm^2)	Stress (t/cm^2) Upper Yield	Lower Yield	Ultimate	Strain* (%) ε_{sh}	ε_b	
0.005	0.0053	1.29	1983	3.43	3.25	4.93	2.12	30.7	m. v.**
	0.0001	0.01	25	0.05	0.04	0.11	0.05	0.8	s. d.
0.5	0.498	1.29	1984	3.71	3.52	4.96	2.28	28.3	m. v.
	0.031	0.005	45	0.07	0.07	0.11	0.25	0.7	s. d.
5.0	4.71	1.29	1980	3.89	3.73	5.08	2.90	31.4	m. v.
	0.45	0.01	73	0.09	0.06	0.03	0.09	1.0	s. d.
10.0	9.69	1.29	1993	3.94	3.79	4.97	3.06	30.4	m. v.
	0.53	0.01	42	0.11	0.13	0.33	0.14	0.8	s. d.

* ε_{sh} : strain at beginning of strain-hardening ** m. v. : mean value
ε_b : strain at breakage s. d. : standard deviation

Table 5 Summary of Test Results of Deformed Bars

Nominal Strain Rate (%/sec)	Strain Rate (%/sec)	Elastic Modulus (t/cm^2)	Stress (t/cm^2) Upper Yield	Lower Yield	Ultimate	Strain* (%) ε_{sh}	ε_b	
0.005	0.0054	1745	3.05	2.90	4.94	1.35	29.1	m. v.**
	0.0002	24	0.04	0.04	0.08	0.12	0.5	s. d.
0.5	0.545	1755	3.24	3.09	4.94	1.55	27.6	m. v.
	0.029	52	0.05	0.03	0.07	0.05	0.4	s. d.
5.0	5.13	1758	3.53	3.41	5.20	1.86	30.1	m. v.
	0.72	36	0.05	0.05	0.02	0.17	1.9	s. d.
10.0	9.03	1740	3.66	3.41	5.20	1.82	28.9	m. v.
	0.47	52	0.09	0.07	0.10	0.14	1.4	s. d.

* ε_{sh} : strain at beginning of strain-hardening ** m. v. : mean value
ε_b : strain at breakage s. d. : standard deviation

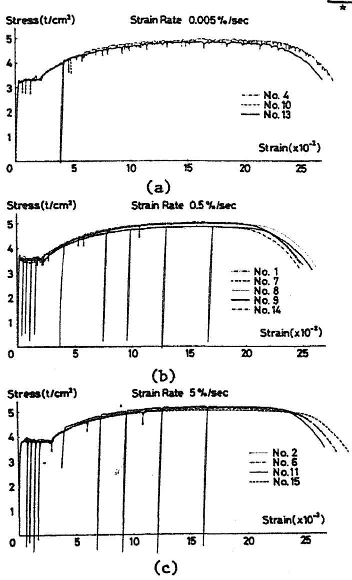


Fig. 11 Stress-Strain Curves of Steel Bars

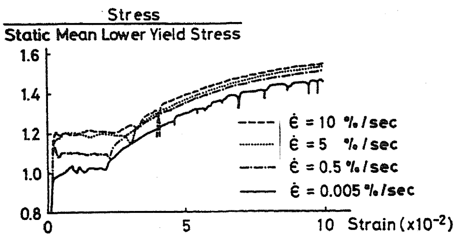


Fig. 12 Stress-Strain Curves near Yield Plateau Region

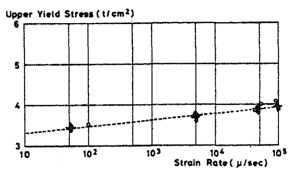


Fig. 13 Upper Yield Stress

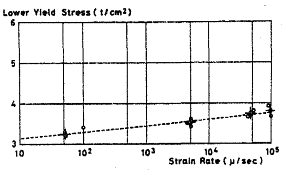


Fig. 14 Lower Yield Stress

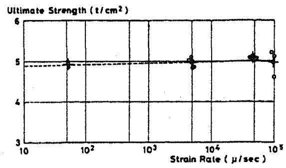


Fig. 15 Ultimate Strength

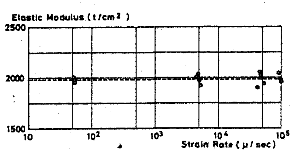


Fig. 16 Elastic Modulus

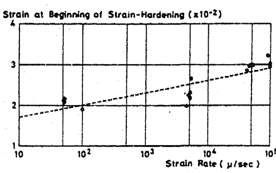


Fig. 17 Strain at Beginning of Strain-Hardening

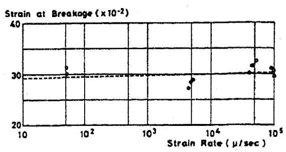
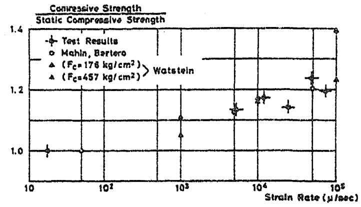


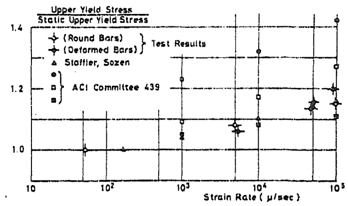
Fig. 18 Strain at Breakage

ing strain rates. A strain rate has little or no effect on the strain at breakage as shown in Fig. 18.

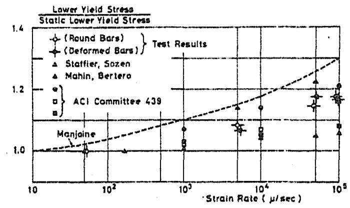
It is concluded that stress in the yield plateau region and strain at the beginning of strain-hardening become larger by applying force dynamically, but a strain rate has slight influence in strain-hardening region.



(a) Compressive Strength of Concrete



(b) Upper Yield Stress of Steel



(c) Lower Yield Stress of Steel

Fig. 19 Comparison with Reference Data

Comparison with Reference Data Plots of the test results compared with the data from the references 1), 2), 3) and 4) are shown in Fig. 19, which shows the relationships between the strain rate and the ratio of compressive strength of concrete, and upper yield stress or lower yield stress of steel bars to quasi-static stress. All data are scattering in comparatively narrow region and have the same characteristics.

EFFECT OF LOADING RATE ON THE BEHAVIOR OF STEEL BEAMS

Theoretical Investigation Based on the results of the material tests, stress-strain relationship of steel under dynamic loading is formulated. Yield stress and ultimate strength of steel are assumed to increase linearly with the logarithm of a strain rate. When the assumption of plane distribution of strain is made and the beam is subjected to monotonic bending moment at the prescribed curvature rate, the stress distribution in a section can be determined by the two quantities, those are strain ε and strain rate $\dot{\varepsilon}$, using the formulated stress-strain relationships. In Fig. 20, typical bending moment-curvature curves for an H-shaped (H-50x50x6x6) cross section are plotted at elevated curvature rates, where M_p is the full plastic moment and $\phi_p = M_p/EI$ (EI is the elastic flexural stiffness).

Experimental Investigation Four test beams are 600 mm long with a cross section H-50x50x6x6, as shown in Fig. 21, which were built-up by welding SS 41 steel plate and annealed. Simply-supported beams were loaded with symmetrical two points by servo-type machine. Relative displacement δ shown in Fig. 22 was measured by differential transformers. The rate of a relative displacement which was equivalent to a curvature rate was planned to keep the prescribed value. Mechanical properties of the used materials obtained from quasi-static tensile tests are shown in Table 6. Measured dimensions of the specimens are listed in Table 7. Fig. 23 shows plots of load versus relative displacement obtained experimentally and analytically, using the average rate near initial yielding region. Fig. 24 shows a plot of load versus the curvature rate. It is observed that the load carrying capacity of the beam in the dynamic monotonic loading test increases compared with that in the quasi-static loading test. The theoretical analysis predicts the increase of the load carrying capacity but is not sufficient quantitatively.

EFFECT OF LOADING RATE ON THE BEHAVIOR OF REINFORCED CONCRETE BEAMS

<u>Theoretical Investigation</u>   Stress-strain relationships of concrete and steel reinforcing bars under dynamic loading are formulated based on the results of the material tests. Compressive strength of concrete is assumed to increase linearly with the logarithm of a strain rate. The stress-strain

Table 6 Mechanical Properties of Material

	Elastic Modulus	Yield Stress	Ultimate Stress	Strain at Breakage
Flange	2120 t/cm^2	2.71 t/cm^2	4.23 t/cm^2	31.5 %
Web	2140 t/cm^2	2.64 t/cm^2	4.16 t/cm^2	31.7 %

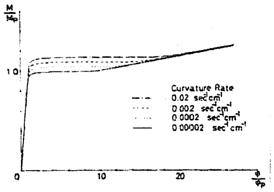


Fig. 20

Moment-Curvature Diagram

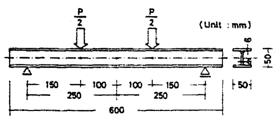


Fig. 21

Test Specimen of Steel Beam

Table 7 Measured Dimensions of Steel Beams

	Depth	Width	Thickness	
			Web	Flange
for Static Test	49.85	49.74	5.99	5.97
for Dynamic Test	49.95	49.84	5.97	5.93

(unit:mm)

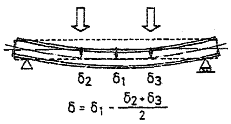


Fig. 22

Measuring Displacement

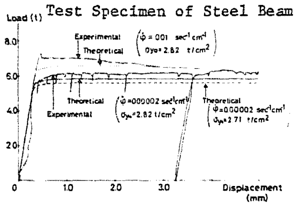


Fig. 23 Load-Displacement Diagram

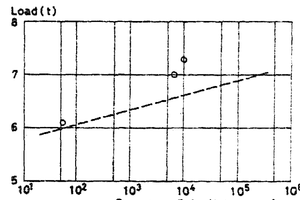


Fig. 24

Load-Curvature Rate Diagram

Table 8 Mix Proportions for Reinforced Concrete Beams

	Normal Portland Cement	Sand, smaller than 1.2 mm in sieve size	Gravel, size from 5 mm to 10 mm	Water-Cement Ratio, by weight	Slump
Specific Gravity	3.15	2.54	2.58	60 %	15 cm
Mix Proportions by weight	1	3.06	2.50		

Table 9 Mechanical Properties of Material

Steel Bars	
Yield Stress	2.44 t/cm^2
Ultimate Strength	3.73 t/cm^2
Strain at Breakage	43 %
Concrete	
Compressive Strength	215 kg/cm^2
Strain at Maximum Stress	0.215 %

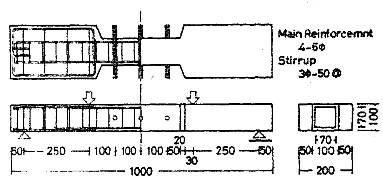


Fig. 25 Test Specimen of Reinforced Concrete Beam

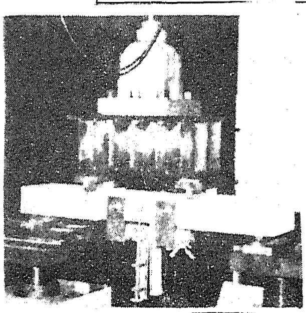


Photo 1 View of Test Set-Up

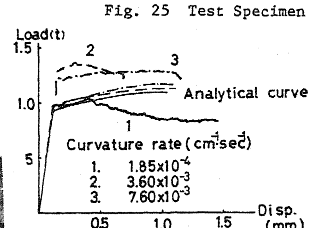


Fig. 26 Load-Displacement Diagram

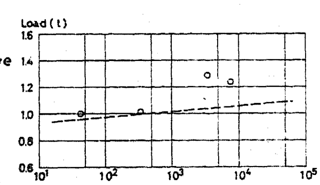


Fig. 27

Load-Curvature Rate Diagram

relationship for concrete is assumed by a parabolic function, and that for steel is identical with that of the previous section.

Experimental Investigation   Four specimens of doubly reinforced concrete beams with a 100x100 mm square cross section, as shown in Fig. 25, were tested. Mix proportions of concrete and mechanical properties of concrete and steel bars are listed in Tables 8 and 9. Age of specimens at test was 42-52 weeks. Load was applied monotonically so that the rate of the vertical relative displacement between the mid-point and the points 100 mm distant from the mid-point was kept constant. The view of the test is shown in Photo 1. Figs. 26 and 27 show plots of load versus relative displacement and curvature rate, respectively, obtained experimentally and analytically. The load carrying capacity of the reinforced concrete beam under dynamic loading increases with increasing curvature rate but is considerably higher than that predicted by the analysis.

CONCLUSIONS

On the basis of the experimental and analytical results, the following remarks can be drawn.

1) Compressive strength of concrete increases with increasing strain rate. However, a geometrical configuration of a stress-strain curve and the strain at the maximum stress are hardly affected by a strain rate. Yield stress of steel bar increases with increasing strain rate but the behavior in the strain-hardening region is not affected largely by a strain rate.

2) Bending moment bearing capacities of steel and reinforced concrete beams increase also with increasing curvature rate. Analysis predicts the increase qualitatively but is not sufficient quantitatively.

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