EFFECTS OF DISPLACEMENT RATES ON THE BEHAVIOR OF STEEL BEAMS AND COMPOSITE BEAMS

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SUMMARY

How the difference of displacement rates influences elastic-plastic behaviors of structural members is investigated by dynamic tests and quasi-static tests. The monotonic and cyclic reversed tests of steel beams and composite beams are performed under the control of the displacement rates. The maximum moment capacities of members are recognized to increase as the displacement rate increases. Further, stiffnesses and deformation capacities of members are discussed in relation to the displacement rates. The viscous damping in an elastic range of members is also described to explain the increases in the maximum moment capacities.

INTRODUCTION

In the investigation of structural or member behaviors under earthquake motion, static monotonic and repeated tests have been mainly employed for many years. Recently pseudo-dynamic response analyses of structures have been carried out by computer-load test apparatus hybrid on-line system$^{1)}$. In these analyses, tests are also statically performed due to technical problems or for a measurement convenience. Taking into consideration a fact that structures respond to earthquakes dynamically, however, dynamic behavior presumption based on static test data may involve inappropriate factors. Therefore, an explication of whether or not and how static test results are discrepant from dynamic test results makes it possible to confirm the reliability of those results and to ascertain relationship between data from the two tests.

Static and dynamic hysteresis curves are compared according to the above-mentioned view in some reports$^{2) - 7)}$. A larger portion of those reports are concerned with studies of material properties rather than those of structural or member behaviors. This paper deals with quasi-static and dynamic tests of realistic size steel beams and fully composite beams with steel deck subjected to monotonic and cyclic loadings, and investigates how the difference of displacement rates affects 1) Maximum moment capacity, 2) Elastic stiffness and stiffness under unloading in plastic range and 3) Deformation capacity and shape of hysteresis loop. Furthermore, a viscous damping in an elastic range of steel beams is evaluated, and an increase in moment capacities due to a viscous damping is examined.

TEST SPECIMENS

The tests were performed in five steel beams and five fully composite beams.

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Considering the best-possible elimination of scale factor effects and an actuator capacity, half-size members were designed. A beam and a column stub of composite beam specimens were fabricated from a W 8 x 13 (H-202.9 x 101.6 x 5.84 x 6.48) section and a W 8 x 35 (H-206.2 x 203.7 x 7.87 x 12.57) section, respectively. The length of the specimen from the face of the column stub to a support point was 1.35 m long and represented the distance to the point of contraflexure. Full penetration butt weld was used for joining beam flanges to column flanges and fillet weld for joining beam webs to the column flanges. The steel deck, dimension of which was D. 𝕃 -50 x 40 x 25 x 0.8, was oriented perpendicular to the steel beam and was split on the top flange of the steel beam.

A shear connection was designed according to ultimate strength design. The number and spacing of headed studs between the loading point and the face of the column stub were determined so as to resist the maximum horizontal shear. The 1,000 x 65 concrete slab was cast on the top flange of the steel beam. For slab reinforcement, 6 mm diameter steel bars were latticed at 17 mm deep from the slab surface with the spacing of 100 mm.

Steel beam specimens were identical with the composite beam specimens except for the concrete slab. Table 1 shows the mechanical properties of flanges and webs of the steel elements of specimens. The slab was made of lightweight concrete. Three cylinders were tested to obtain the strength of the concrete on the same day the composite beam specimens were tested. The mean strength of the concrete was 204.3 kg/cm^2.

TEST SETUP

Fig. 1 indicates the test setup schematically. A concentrated monotonic or cyclic load was applied to each beam specimen through the central column stub. The specimens were simply supported and were not allowed to move laterally at both ends. The column stub was also prevented from lateral movement by the supports, but its free rotation about the column axis was allowed. The top of the column stub was loaded by means of the servo-controlled hydraulic actuator which had a capacity of ±20 tons dynamically and a maximum stroke of ±150 mm.

LOADING PROGRAM AND DISPLACEMENT RATES

A sequence of the cyclic loadings was selected so that positive deflection amplitude may be equal to negative one. The magnitude of deflection amplitudes, δ, at the loading point was determined in such a way that beam rotation, θ, which was defined as δ/ℓ (ℓ: beam span between the support point and the face of the column stub) became the multiple of the rotation, ${}_s\theta_p$, which was defined as ${}_s\theta_p = {}_sM_p\ell/3EI$ (${}_sM_p$: full plastic moment of steel beams and steel element of composite beams, EI: flexural rigidity). The deflection amplitudes were progressively increased in the subsequent cyclic tests. The number of load reversals was four cycles in each deflection amplitude.

Three kinds of displacement rates were adopted, which were controlled at the loading point. Their nominal rates were 0.15 cm/sec for quasi-static tests and 15 cm/sec and 30 cm/sec for dynamic tests. Fig. 2 shows a time history of the displacement at the loading point. In the Figure, ${}_s\delta_p$ equals $\ell\,{}_s\theta_p$. Table 2 summarizes the details of loading program and the displacement rates of each specimen. In the Table, specimens S1 to S5 represent those of steel beams and specimens C1 to C5 those of composite beams.

MEASURING INSTRUMENTATION AND LOADING

Relative displacement between the loading point and the support point was measured by means of displacement transducers to determine the rotation, θ, of the beam specimens. The applied load was measured by a load cell built into the actuator. Both loading and collecting test data were controlled by a mini-computer which was connected directly to the actuator system. A displacement signal, which was programmed to generate a displacement-time relationship as shown in Fig. 2, was input into the actuator controller through a D/A converter under computer command. On the other hand, the data obtained from the experiment were stored in magnetic tape through A/D converters. This operation was also carried out by the same computer in parallel with the loading.

TEST RESULTS AND REMARKS

The moment-rotation relationships of the specimens are shown in Figs. 3 to 5. Of those figures, Fig. 3 shows the monotonic curves of the steel beams (S1 & S2) and the composite beams (C1 & C2). Figs. 4 and 5 indicate the hysteresis loops for cyclic tests of the steel beams (S3, S4 & S5) and the composite beams (C3, C4 & C5), respectively. Moment, M, is the applied beam moment at the face of the column stub and is normalized by the full plastic moment, ${}_sM_p$, of the steel element. On the other hand, beam rotation, θ, is normalized by the rotation, ${}_s\theta_p$.

The strain rate at a point on the beam flange which is 10 cm off the column flange face is calculated from the measured strain on the same beam flange. Fig. 6 gives the strain rate of steel specimen S5 in the elastic-plastic range. The specimen was repeatedly loaded with the displacement rate V = 28.2 cm/sec, and the deflection amplitude, $\theta = 2.35\ {}_s\theta_p$. Fig. 6 (a) shows the time history of the strain rate and Fig. 6 (b) the relationship between the moment and the strain rate. The strain rate is about 45,000 to 50,000 μ/sec in the elastic range and the maximum strain rate about 200,000 μ/sec in the plastic range. The broken line in Fig. 6 (a) drawn according to the strain rate in the elastic range represents the time history of the strain rate assuming that the steel beam behaves elastically at V = 28.2 cm/sec. The strain rate of the specimen S4 at V = 14.3 cm/sec was about half the above values both in the elastic and in the plastic ranges. In case of quasi-static test, specimen S3, the strain rate was about 220 μ/sec in the elastic range, and the maximum strain rate about 1,200 μ/sec in the plastic range.

Fig. 7 indicates the relationship between the logarithm of the displacement rate, V, and maximum beam moment capacity, $m_{max} = M_{max}/{}_sM_p$, at the face of the column stub. The maximum beam moment capacities were defined as follows: in monotonic tests, it was the maximum moment capacity recorded under the loading; in cyclic reversed tests, it meant the positive and negative maximum capacity of the "stable" hysteresis loops obtained from the first cyclic loading in each test, for example, deflection amplitude of 2.33 ${}_s\theta_p$ in specimen S3 and deflection amplitude of 3.92 ${}_s\theta_p$ in specimen C3. Fig. 8 shows the relationship between the displacement rate, V, and the ratio of the maximum moment capacity, $m_{max}^{dynamic} = M_{max}^{dynamic}/{}_sM_p$, in dynamic loadings to the maximum moment capacity, $m_{max}^{static} = M_{max}^{static}/{}_sM_p$, in quasi-static loadings.

The differences of elastic stiffness between quasi-static and dynamic loadings were not observed in both steel beams and composite beams. It was demonstrated by Fig. 3, which showed the moment-rotation curves of monotonic tests, and Figs. 4 and 5, which showed the hysteresis curves of the cyclic reversed tests. Figs. 4 and 5 also made it clear that there were no differences of stiffness under unloading in the plastic range between the two loadings in both beams.

According to the conventional method in monotonic test and the method defined by authors in cyclic test before, the rotation capacity, R, of the beam specimens was calculated by $R = (\theta/{}_s\theta_p)_{max} - 1$8), 9). In the equation, $(\theta/{}_s\theta_p)_{max}$ was defined as the beam rotation corresponding to the maximum moment in monotonic tests of steel beams, and in cyclic tests of steel beams and composite beams, defined as the maximum "stable" rotation amplitude, beyond which beams failed. The rotation capacities are summarized in Table 2. In the Table, symbol, >, means that the rotation capacity is larger than that presented in the Table.

An increase in the maximum moment capacity of steel beams in association with an increase in displacement rates is investigated on the assumption that it is caused by viscous damping of beams. In this paper, an examination is made of an extent to which the viscous damping obtained from the elastic tests of steel beams contributes to the increase in the maximum moment capacities. In the tests, a load, P, is supposed to be $P = c\dot{x} + kx$, where c means the viscous damping constant, $\dot{x}$ the displacement rate at the loading point, x the displacement at the loading point, and k a stiffness of beams. Constant deflection amplitude cyclic tests are conducted at three nominal displacement rates of 1.25 cm/sec, 5 cm/sec and 10 cm/sec within the elastic range. The viscous damping constant c is 0.0151 to 0.0205 t·sec/cm from the calculation of the above equation and the hysteresis loops in the tests. These results reveal that there is almost no increase in the moment capacity due to the viscous damping, in case of the displacement rate, V = 0.15 cm/sec. Therefore, the moment capacity of test specimen S5 at V = 28.2 cm/sec would increase from that at V = 0.15 cm/sec by 5 to 7 % of the full plastic moment, ${}_sM_p$. In the actual test, the rate of the increase turns out to be 12 % of the full plastic moment.

CONCLUSIONS

The results of the tests revealed that the shape and the characteristics of the hysteresis loops were affected by the displacement rates. The following conclusions can be drawn from them in relation with the displacement rates:

1. Maximum moment capacities of steel beams and composite beams increase as a displacement rate increases. This was proved in both monotonic and cyclic reversed loadings. The largest increase in the maximum moment capacity of the dynamic loading from that of the quasi-static loading is about 20 % in the monotonic positive moment test of the composite beam. On the other hand, the smallest increase therein is about 5 to 8 % in the cyclic negative moment test of the composite beams. In case of the steel beams, increases are about 16 % in the monotonic test and about 11 % in the cyclic test.
2. The displacement rate does not affect the elastic stiffness for monotonic loadings nor the stiffness under unloading in the plastic range for cyclic loadings regardless of steel beams and composite beams.
3. Though a detailed description was not made in this investigation, steel beams show a tendency to slightly increased rotation capacities as a displacement rate increases, but in case of composite beams there is no clear increase or decrease in rotation capacities even if a displacement rate increases.
4. In the cyclic test of the steel beam at the displacement rate V = 28.2 cm/sec, the strain rate on the beam flange near the column flange is about 45,000 to 50,000 μ/sec in the elastic range and the maximum strain rate about 200,000 μ/sec in the plastic range.

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Table 1 Material Properties of Steels

Specimen	σ_y(t/cm^2)	σ_{max}(t/cm^2)	ε_{st}(x10^{-3})	E_{st}(t/cm^2)	ε_B(%)
Flange	2.82	4.18	18.9	36.1	27
Web	3.72	4.74	18.0	32.5	23

Table 2 Summary of Test Results

Specimen	Loading Condition	Displacement Amplitude($_s\theta_p$)	No.of Cycle	Displacement Rate(cm/sec)	Rotation Capacity
S1	Monotonic			0.14	5.25
S2	Monotonic			30.3	7.0
S3	Cyclic	2.33	4	0.14	1.87
		2.87	4	0.14	
		2.98	4	29.8	
		2.87	4	0.14	
		3.30	4	0.14	
S4	Cyclic	2.37	4	14.3	> 2.43
		2.92	4	14.6	
		3.43	4	14.7	
		3.99	4	15.0	
S5	Cyclic	2.35	4	28.2	> 2.38
		2.93	4	29.3	
		3.38	4	28.9	
C1	Monotonic			0.15	
C2	Monotonic			30.2	
C3	Cyclic	3.92	4	0.15	2.92
		4.43	4	0.15	
C4	Cyclic	3.98	4	14.9	2.98
		4.57	4	15.2	
C5	Cyclic	4.02	4	30.2	3.02
		4.68	4	31.2	

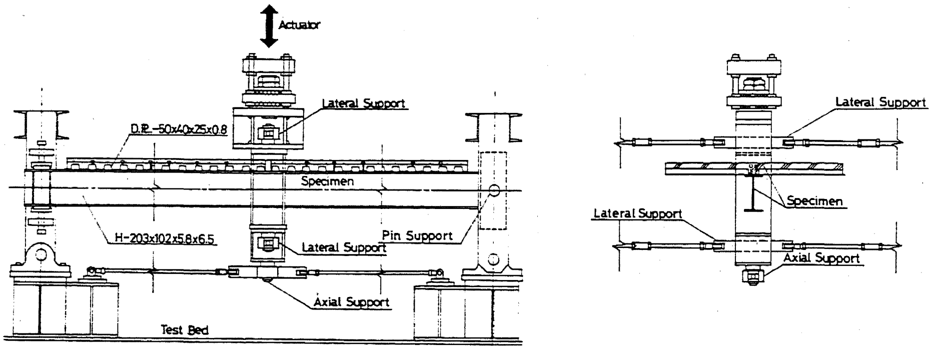


Fig.1 General View of Test Setup

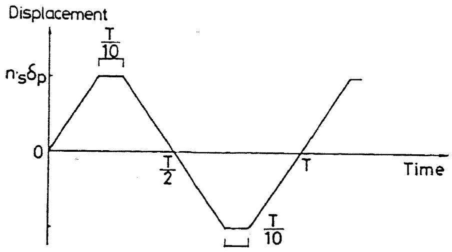


Fig.2 Time History of Applied Displacement

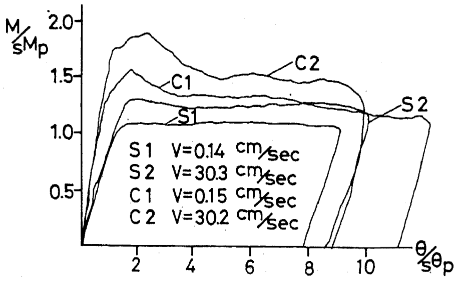
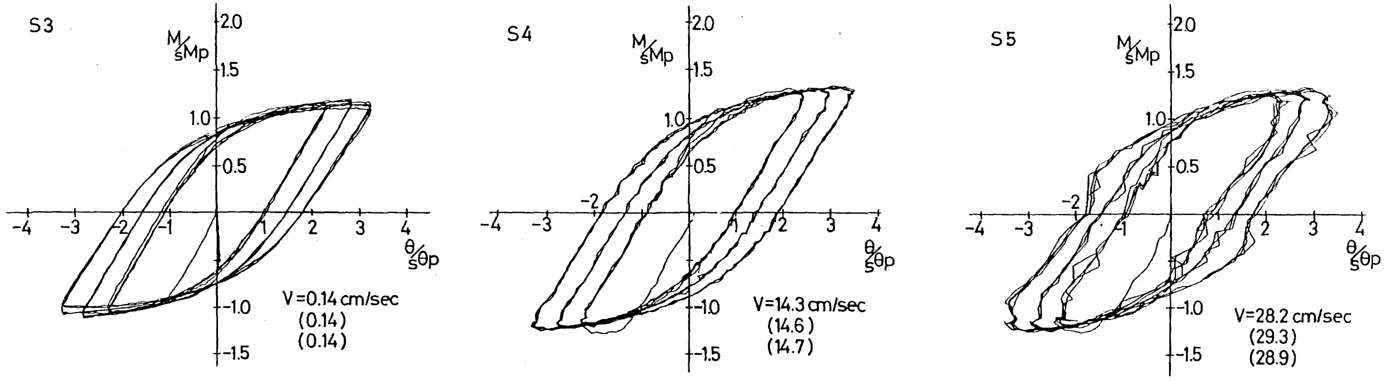
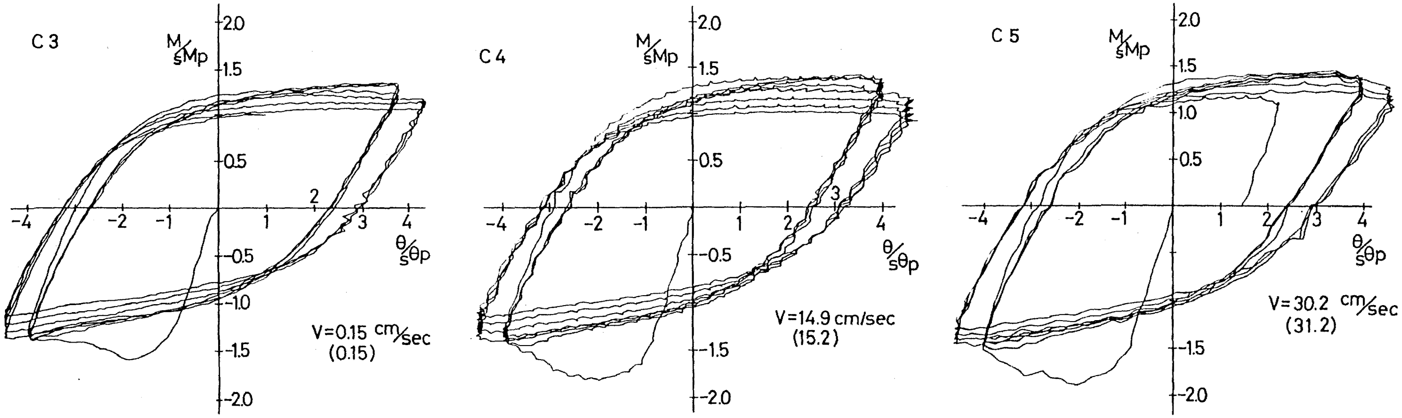


Fig.3 Moment and Rotation Curves



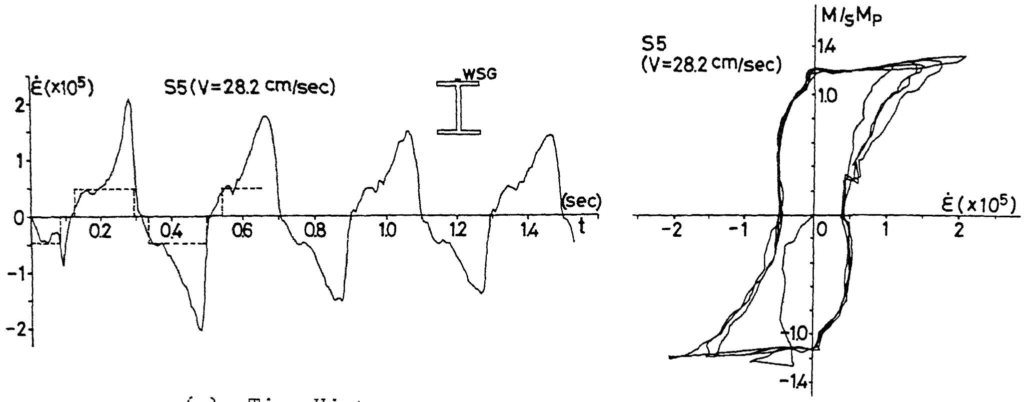
(a) Specimen S3 (b) Specimen S4 (c) Specimen S5

Fig.4 Hysteresis Loops of Steel Beams



(a) Specimen C3 (b) Specimen C4 (c) Specimen C5

Fig.5 Hysteresis Loops of Composite Beams



(a) Time History

(b) Moment and Strain Rate

Fig.6 Strain Rate (Specimen S5)

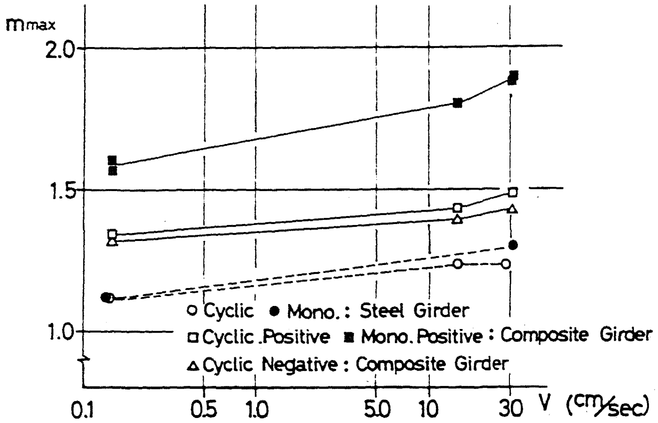


Fig.7 Displacement Rate and Maximum Moment

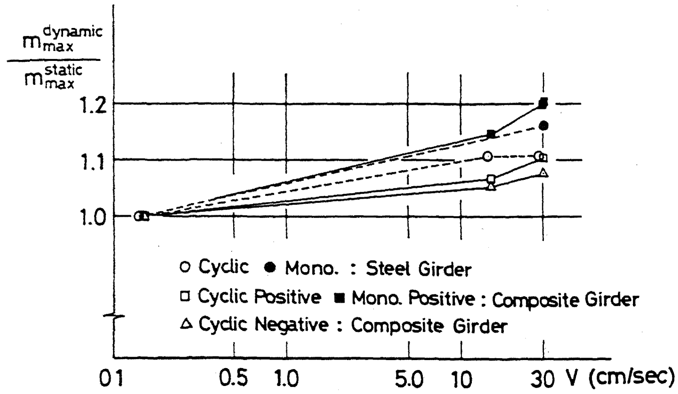


Fig.8 Displacement Rate and Ratio of Maximum Moment in Dynamic Tests to Maximum Moment in Quasi-Static Tests