Effects of Loading Rate on Reinforced Concrete Beams

Min Li & Hongnan Li
Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, China

SUMMARY:
The effects of loading rate on the reinforced concrete beams are experimentally studied in the present paper. Firstly, the effects of strain rate on the different grades of concrete are investigated using the electro-hydraulic servo-controlled testing system at the strain rate that might be experienced during earthquakes. Based on the test results, the dynamic increasing factors (DIF) of concrete are gotten. Then, the dynamic properties of reinforced concrete beams are studied considering different parameters, including concrete strength (C30 and C50), steel strength (HRB335 and HRB400), shear span ratio(λ=5.5 and λ=3.0), loading rate(0.05mm/s and 30mm/s) and loading mode(monotonic loading and cyclic loading). The effects of loading rate on the bearing capacity, ductility, stiffness, failure mode, and energy absorbing of beams are analyzed. Some conclusions with engineering significance are obtained in terms of experimental results.

Keywords: loading rate; strain rate; reinforced concrete beams; concrete

1. INTRODUCTION

The reinforced concrete structure possibly suffers strong earthquake ground motions during the period of its active service, and the strain rate at critical sections from the dynamic loads may be as high as 0.1/s. The properties of structural materials under dynamic loading will be different from static loading. While the provisions for the seismic design in current design codes (GB 50011.2010) are developed on the basis of the results obtained from the quasi-static tests, and the rate-dependent properties of structural materials haven't been considered, it may be because that the studies on the rate-dependent properties of steel and concrete and the effects of rate-dependent properties of materials on reinforced concrete members and structures are insufficient and inconclusive.

Up to now, some researches on the effects of strain rate on the steel or concrete materials have been conducted. The general conclusions are that, when strain rate increases, the yield strength and ultimate strength of steel enhance, the compressive strength, tensile strength and the slope of the descending portion of the stress-strain curve of concrete increase also, and the strain-rate effects are inversely proportional to the strength of steel or concrete.

While, there are a few studies on the effects of loading rate on reinforced concrete members. The results gotten by Bertero et. al.(1973), Mutsuyoshi and Machida (1984) are that, when loading rate increased, the yield strength of beam increased at the first yielding of the reinforcement, however, the ultimate strength was not effected by the loading rate. Shah et al. (1987) found that the faster loading rate induced higher increment in the ultimate strength and damage, larger reduction in stiffness, and higher amount dissipation in energy. Kulkarni and Shah (1998) found that when loading rate increased, the bearing capacity of beam increased, and the failure mode of some beams changed from the shear failure at lower rate to the flexural failure at higher rate. As there are inconsistent ideas on the loading rate effects on reinforced concrete members, with the aim of obtaining further information, experimental investigations are undertaken in the present paper.

In this paper, the effects of loading rate on the reinforced concrete beams are experimentally studied. Firstly, the effects of strain rate on the concrete of the grades C30 and C50 were investigated at the strain rate (10^{-5}/s～0.1/s) that might be experienced during earthquakes. Then, the dynamic responses of reinforced concrete beams under monotonic and cyclic loading at two loading rates of 0.05mm/s and 30mm/s were investigated. The effects of loading rate on the bearing capacity, ductility, stiffness, failure mode, and energy absorbing of beams are analyzed, and some important conclusions are given.

2. DYNAMIC TEST OF CONCRETE

Uniaxial compressive strength of concrete with the grade C30 and C50 was tested using the electro-hydraulic servo-controlled testing system (shown in Fig.3.2) at different loading rates. The machine has an axial tensile capacity of 1000 KN and compressive capacity of 2500 KN, the hardware allows it to achieve a "no-load" piston velocity of about 56mm/s, and the stroke range is ±100mm. Mix proportions of concrete used in this test are given in Tab.2.1. The dimension of specimen was 100mm×100mm×100mm, and these cubic specimens were naturally cured simultaneously with the reinforced concrete beam specimens. Displacement control was used and the loading rate was constant during loading. Four typical strain rates, which were 10^{-5}/s、10^{-4}/s、10^{-3}/s and 10^{-2}/s, were applied, and every strain rate had three tests at least. Tab.2.2 gives the mean compressive strength of the grade C30 and C50 concrete at different strain rates. It can be seen that, with the strain rate increasing, the compressive strength of concrete augments, and the grade C30 concrete is more sensitive to strain rate than the grade C50 concrete. Based on the results, the DIF (dynamic increasing factor) of compressive strength of grade C30 concrete is gotten by the regression analysis as follows:

$$\frac{f_{cd}}{f_c} = 1.0 + 0.0648\lg\left(\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_{c0}}\right) \tag{2.1}$$

The DIF of compressive strength of grade C50 concrete is obtained as follows:

$$\frac{f_{cd}}{f_c} = 1.0 + 0.0314\lg\left(\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_{c0}}\right) \tag{2.2}$$

Where, $\dot{\varepsilon}_c$ implies the strain rate of concrete, $\dot{\varepsilon}_{c0}$ denotes the quasi-static strain rate of concrete, f_c and f_{cd} mean the quasi-static and dynamic compressive strength of concrete.

Table 2.1 Mix proportions of concrete used in this test

Concrete grade	Cement (kg/m^3)	Sand (kg/m^3)	gravel (kg/m^3)	Water (kg/m^3)	Fly ash (kg/m^3)	Water reducer (kg/m^3)
C50	440	657	1045	185	70	15.3
C30	350	777	1030	143	65	5.0

Table2.2 Mean compressive strength of the grade C30 and C50 concrete at different strain rates

Strain rate(1/s)	C30 (Mpa)	C50 (Mpa)
10^{-5}	36.94	49.22
10^{-4}	39.58	50.84
10^{-3}	41.58	52.42
10^{-2}	44.13	53.77

3. DYNAMIC TEST OF REINFORCED CONCRETE BEAM

3.1. Specimen Design

Sixteen beams were fabricated in the experiment and the dimensions of the beams were identical , as shown in Fig.3.1. The length of the beam was 2500mm, the cross section was 150mm×250mm, and the protective layer thickness was 30mm. The diameter of longitudinal reinforcement was 18mm, and the longitudinal reinforcement ratio was 1.6%; the diameter of stirrup was 6.5mm, the yield strength of stirrup was 388.9MPa, the stirrup spacing was 200mm, and the stirrup ratio was 0.22%. The considered variables were the grade of concrete(C30 and C50), the grade of longitudinal reinforcement (HRB335 and HRB400), shear span ratio(λ =5.5 and λ =3.0), loading rate(0.05mm/s and 30mm/s), and loading mode (monotonic loading and cyclic loading).The test program of beams is shown in Tab.3.1.

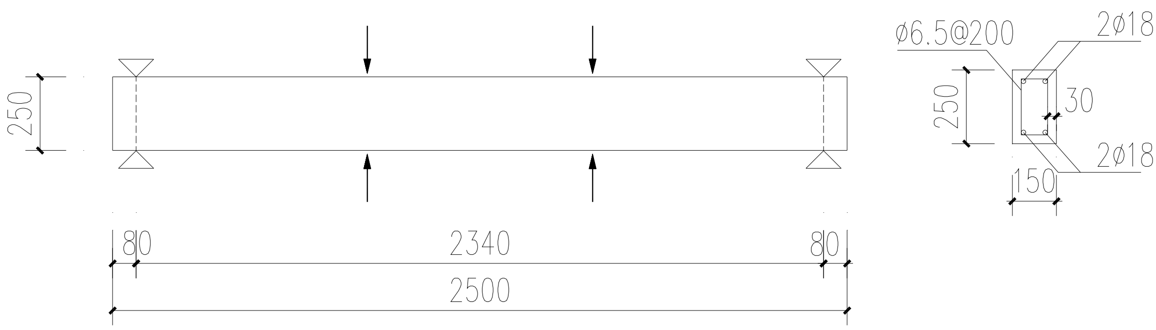


Figure 3.1 Dimension of the beam (unit: mm)

Table 3.1 The test program of beams

Specimen	Concrete cubic compressive strength（MPa）	Yield strength of longitudinal reinforcement (MPa）	Shear Span ratio	Loading rate（mm/s）	Loading mode	Bearing capability（KN）	The ratio of dynamic strength to static strength
B30-MS1	36.94	381.62	5.5	0.05	momotonic	79.95	
B30-MD1	36.94	381.62	5.5	30	momotonic	84.99	6.30%
B30-CS1	36.94	381.62	5.5	0.05	cyclic	76.17/-74.02	
B30-CD1	36.94	381.62	5.5	30	cyclic	79.61/-78.07	4.52%/5.47%
B30-MS2	36.94	381.62	3	0.05	momotonic	137.79	
B30-MD2	36.94	381.62	3	30	momotonic	150.99	9.60%
B30-CS2	36.94	381.62	3	0.05	cyclic	124.88/ -116.73	
B30-CD2	36.94	381.62	3	30	cyclic	133.67/-125.7	7.04%/7.68%
B50-MS1	49.22	428.25	5.5	0.05	momotonic	90.85	
B50-MD1	49.22	428.25	5.5	30	momotonic	94.78	4.30%
B50-CS1	49.22	428.25	5.5	0.05	cyclic	81.00/-79.84	
B50-CD1	49.22	428.25	5.5	30	cyclic	84.14/-83.04	3.88%/4.0%
B50-MS2	49.22	428.25	3	0.05	momotonic	152.03	
B50-MD2	49.22	428.25	3	30	momotonic	162.08	6.61%
B50-CS2	49.22	428.25	3	0.05	cyclic	140.26/-133.85	
B50-CD2	49.22	428.25	3	30	cyclic	146.12/-141.81	4.18%/5.95%

3.2. Test Instruments

Using electro-hydraulic servo-controlled testing system shown in Fig.3.2, the specimens were tested in a three-point or four-point bend configuration. Strains of longitudinal reinforcements at mid-span and stirrups between load point and support point were measured using the strain gauge whose scale distance was 2mm. Strains of concrete at mid-span were measured using the strain gauge whose scale distance was 10mm. Deflections at mid-span were measured by a displacement gauge with a working range of ±100mm, and loads at mid-span were measured by a force sensor with a measuring range of ±500KN. The NI-DAQ data acquisition system, which can record the strain, displacement and load simultaneously, was used to get the real time experimental data.

Figure.3.2 Test instrument

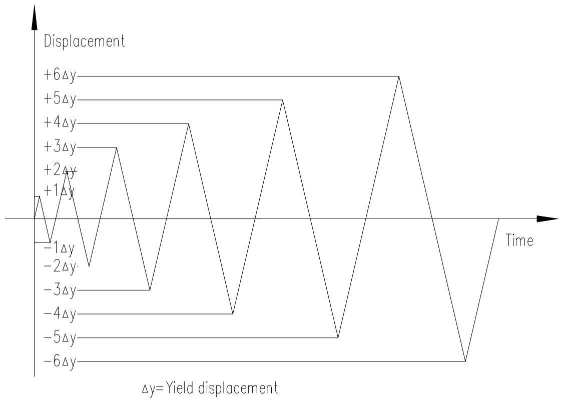


Figure.3.3 Cyclic loading mode

3.3. Loading Procedures

There were two loading modes in this test: monotonic loading and cyclic loading. The displacement amplitudes of cyclic loading were equal to the integer multiples of the yield displacement (Δ_y), which is defined as the mid-span deflection when the longitudinal reinforcement of beam first yields, and only one cyclic was done at a certain amplitude. Cyclic loading mode is shown in Fig.3.3. Displacement control was used and loading rate was constant during loading. Two loading rates of 0.05mm/s and 30mm/s were adopted, 0.05mm/s corresponded to the static tests conducted in general, and 30mm/s corresponded to the dynamic tests excited by earthquake.

3.4. Test Results

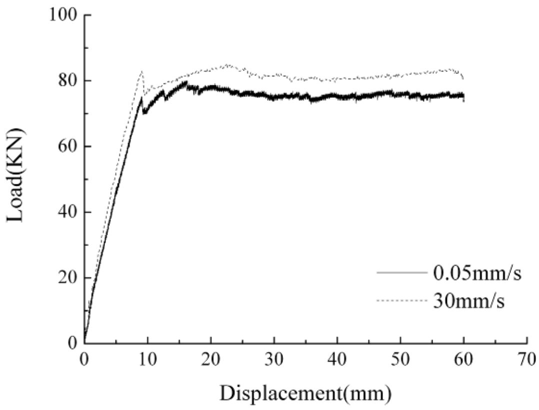
3.4.1. Strain rate

Based on the recorded data by NI-DAQ data acquisition system, the order of strain rate of longitudinal reinforcement at mid-span at slow loading is 10^{-5}/s, and at fast loading is 10^{-3}/s. The order of the maximum strain rate of stirrup is 10^{-3}/s. Thus, the order of strain rate is in the domain of seismic loading (10^{-5}/s~10^{-1}/s), and the study is useful for anti-seismic design.

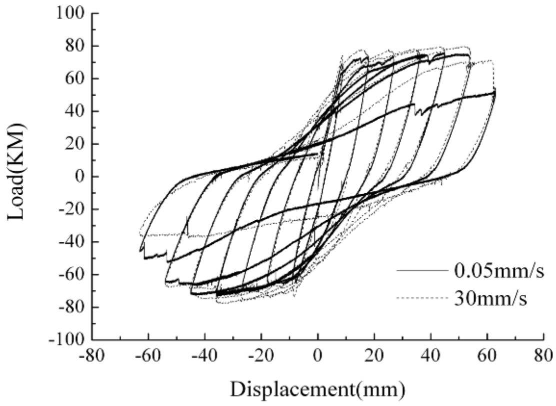
3.4.2. Load-deflection curves

The load-deflection curves of mid-span at different conditions are shown in Fig.3.4, and the bearing capacities of beams at different conditions are shown in Tab.3.1. The results show that, the shape of load-deflection curve at fast loading is similar to that at slow loading. As the loading rate increases, the bearing capacity augments, and higher increment in the bearing capacity for beam with lower strength of materials. As discussion above, the steel and concrete are both rate-dependent materials, and the strain-rate effects are inversely proportional to the strength of materials, therefore, in the absence of inertial effects, the augments of bearing capacity in beams come from the rate-sensitivity of materials.

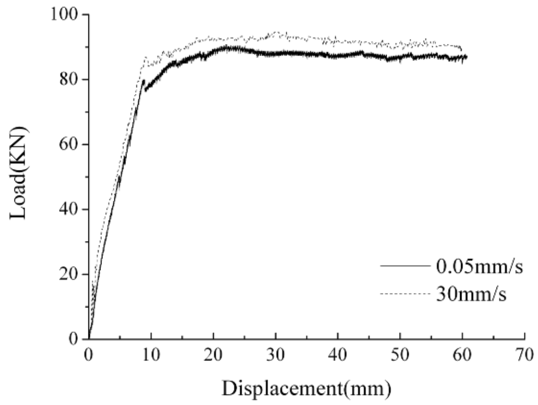
The results also reveal that, for beams with the same material strength, the increment of bearing capacity is inversely proportional to the shear span ratio. It is because that the loading rate is relative to loading points, when the shear span ratio is 5.5, the loading point is in mid span; when the shear span ratio is 3, the distance is 537mm between loading point and mid span. Therefore, although there is same loading rate in loading points, the real loading rate on beams is different, and the real loading rate is higher when the shear span ratio is 3.



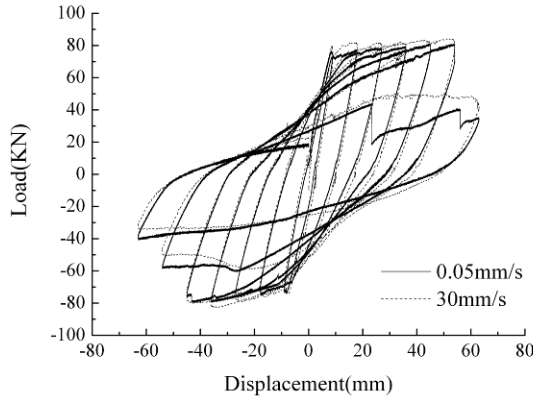
(1) B30-MS1and B30-MD1



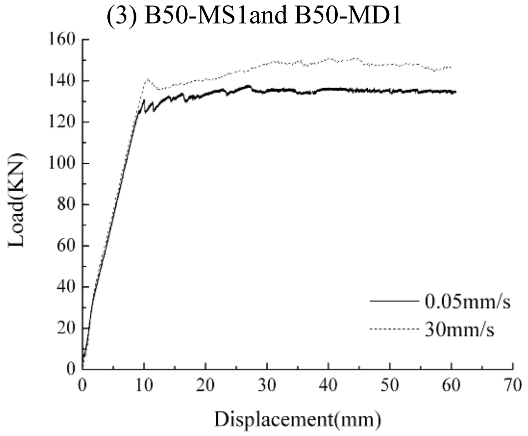
(2) B30-CS1and B30-CD1



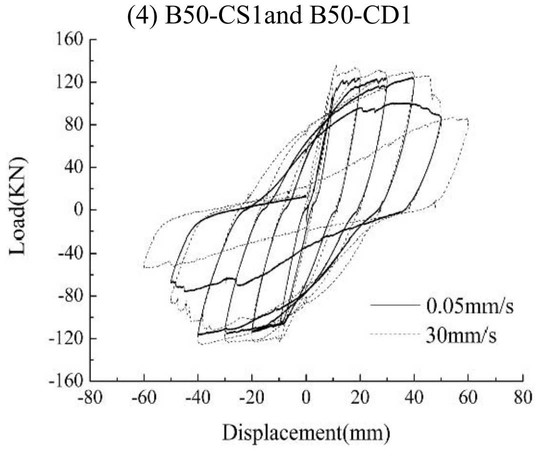
(3) B50-MS1and B50-MD1



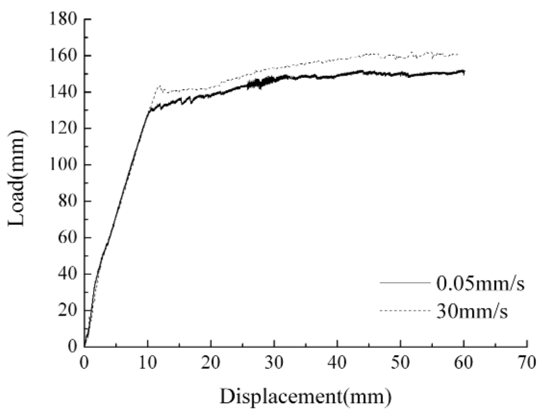
(4) B50-CS1and B50-CD1



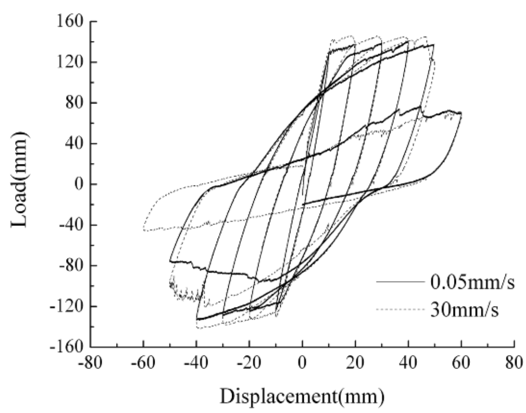
(5) B30-MS2and B30-MD2



(6) B30-CS2and B30-CD2



(7) B50-MS2and B50-MD2



(8) B50-CS2and B50-CD2

Figure 3.4 Load-deflection curves in the mid span of beams at different loading rates

3.4.3. Ductility

Ductility is an important index to reflect the plastic deformability of members and structures. Ductility factor μ_Δ can be used to evaluate the ductility, which is defined as follow

$$\mu_\Delta = \Delta_u / \Delta_y \tag{3.1}$$

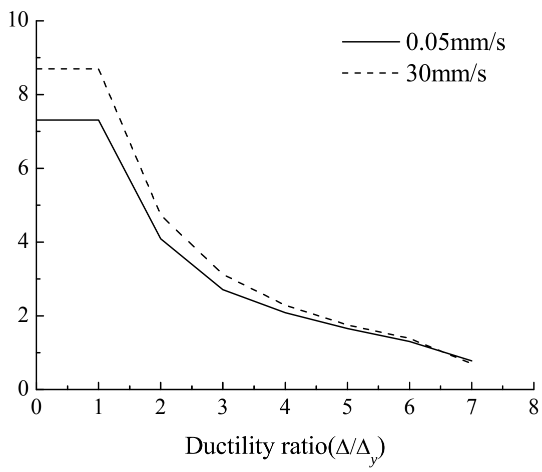
Where, Δ_u means the mid-span deflection when the load reduces to 85% of the ultimate strength and Δ_y denotes the mid-span deflection when the longitudinal reinforcement of beam first yields. Tab.3.2 shows the ductility factors for different specimens, and it can be seen that, for specimens with the same material strength and shear span ratio, the ductility decreases when loading rate increases; for specimens with the same loading rate, the ductility is lower when material strength is higher and shear span ratio is smaller.

Table 3.2 Ductility factors of specimens

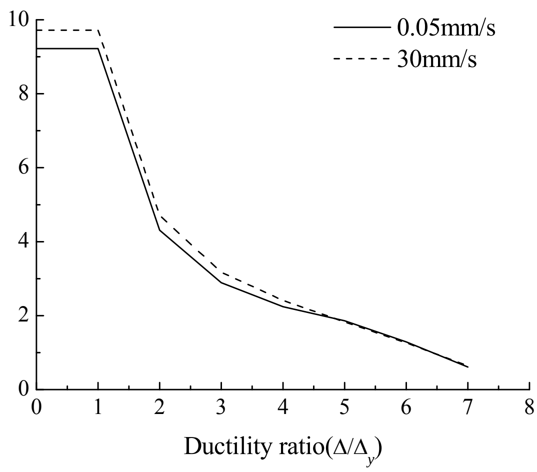
Specimen	Shear span ratio	Loading rate	Δ_y /mm	Δ_u /mm	μ_Δ /mm
B30-CS1	5.5	0.05mm/s	9.27	57.76	6.23
B30-CD1	5.5	30mm/s	9.52	56.83	5.97
B30-CS2	3	0.05mm/s	10.28	44.52	4.33
B30-CD2	3	30mm/s	11.53	49.63	4.3
B50-CS1	5.5	0.05mm/s	9.11	56.03	6.15
B50-CD1	5.5	30mm/s	9.61	56.24	5.85
B50-CS2	3	0.05mm/s	10.78	52.5	4.87
B50-CD2	3	30mm/s	12.7	50.26	3.96

3.4.4. Stiffness

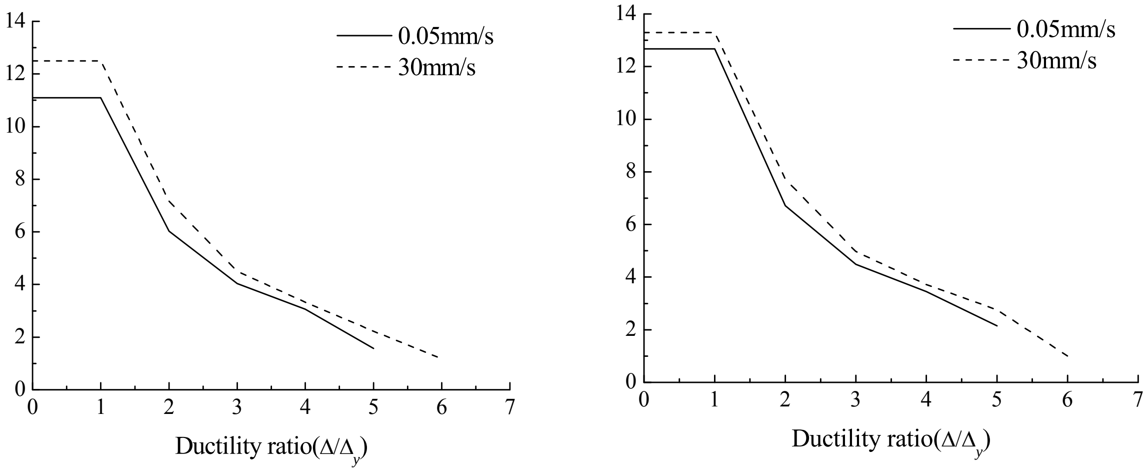
Stiffness of specimen is defined as the diagonal slope of load-deflection hysteretic loop. Stiffness-ductility ratio (Δ / Δ_y) curves of specimens at different loading conditions are shown in Fig.3.5. It is observed that the stiffness decreases when the ductility ratio increases, and the decrease is faster for faster loading rate. A similar conclusion can be deduced from the results reported by Shah et al (1987).



(1) B30-CS1and B30-CD1



(2) B50-CS1and B50-CD1



(3) B30-CS2 and B30-CD2 (4) B50-CS2 and B50-CD2

Figure 3.5 Stiffness-ductility ratio curves at different loading rates

3.4.5. Energy dissipation

In order to evaluate the energy dissipation during cyclic loading, equivalent damping, h_e, is used. It is calculated as

$$h_e = \frac{1}{2\pi} \cdot \frac{S_{(ABC+CDA)}}{S_{(OBE+ODF)}} \tag{3.2}$$

Where, $S_{(ABC+CDA)}$ is the area in the load-displacement hysteretic loop and $S_{(OBE+ODF)}$ means the area under the line BD in Fig.3.6.

Fig.3.7 shows the equivalent damping-displacement curves of specimens under different loading conditions. It can be seen that the equivalent damping is greater for faster loading rate, and the equivalent damping of specimen with higher material strength is less sensitive to loading rate.

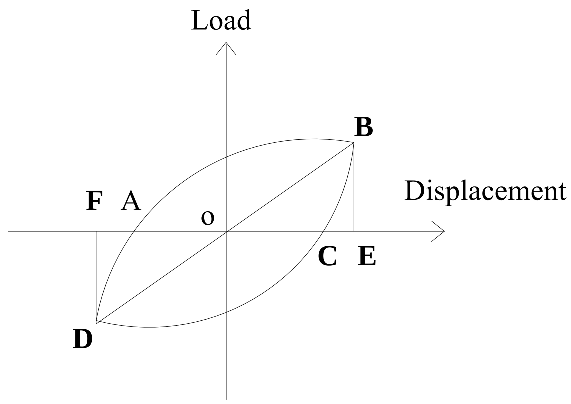


Figure3.6 Load-displacement hysteretic loop

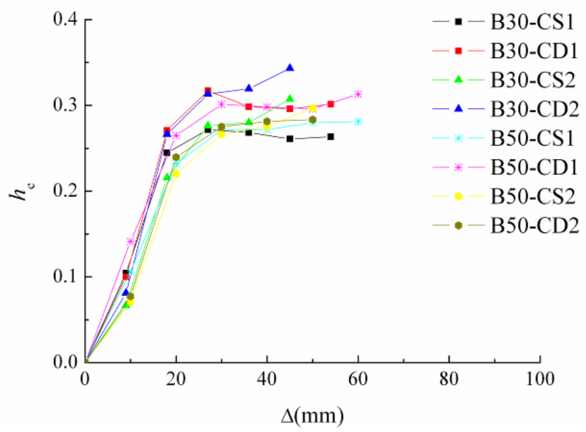
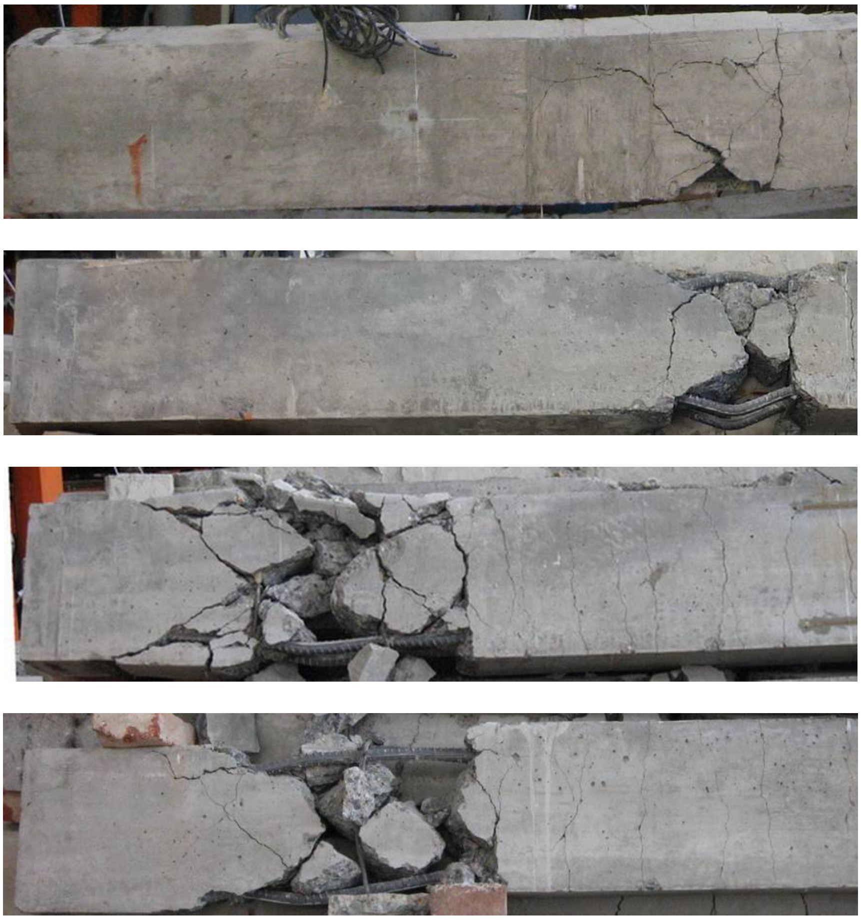


Figure3.7 Equivalent damping-displacement curves

3.4.6. Failure modes

For specimens at monotonic loading, the maximum load didn’t declined when the mid-span deflection was 90mm, considering the safety of the equipment, the tests were stopped and the failure modes weren’t gotten. For specimens at cyclic loading, the failure modes were obtained. Fig.3.8 shows the failure modes of the left half part of beams under different cyclic loading conditions. When the shear span ratio was 5.5, the failure mode was bending failure, x cracks were formed near the loading point and distributed symmetrically about the middle point of beam (shown in Fig.3.8 (1) (2)). When the shear span ratio was 3, the failure mode was shear failure, vertical cracks were formed in the pure bending portion and x cracks were formed between loading point and supporting point, these cracks distributed symmetrically about the middle point of beam also. The space of cracks was greater and the number of cracks was fewer in the pure bending portion at fast loading than those at slow loading (as shown in Fig.3.8 (3) (4)). The reason may be that the transfer of forces between reinforcing bars and concrete is more efficient at slow loading than that at fast loading.



(1) B50-CS1

(2)B50-CD1

(3)B50-CS2

(4) B50-CD2

Figure 3.8 Failure modes of specimens

4. CONCLUSIONS

The effects of loading rate on reinforced concrete beams were experimentally studied in this paper. Based on the test results, some conclusions are gotten.

For concrete, when the strain rate increases, the compressive strength increases, and the increment is inversely proportional to the strength of concrete. For reinforced concrete beams, as the loading rate increases, the bearing capacity augments, and the increment is associated with the strength of materials and shear span ratio; the ductility decreases; the decrease of stiffness is faster; and the equivalent damping increases. Loading rate doesn't change the failure mode of beams, but changes the distribution of cracks.

Altogether, when the loading rate increases, the bearing capacity and the absorbed energy increase, which are beneficial to the structure under seismic load; however, the ductility decreases and the decrease in stiffness becomes fast, which are disadvantages for the structure under seismic load.

What's more, the loading rate can change the distribution of cracks, which should be noticed in anti-seismic design. Due to the limitation of experiment equipment, the dynamic loading rate in this paper isn't fast enough to reach the probable maximum loading rate that may be experienced during earthquake, further experimental studies and numerical simulations are needed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by National Natural Science Foundation of China under Grant No. 90815026 and No.51008040, Foundation of Ministry of Education of China for Innovation Group under Grant No. IRT0518.

REFERENCES

Bertero, V.V., Rea, D., Mahin, S., and Atalay, M.B. (1973). Rate of loading effects on uncracked and repaired reinforced concrete members, *Proceedings of 5th world conference on earthquake engineering*, Rome, 1461- 1470.

GB 50011 (2010). Code for Seismic Design of Buildings, China Architecture & Building press, Beijing, China.(in Chinese)

Kulkarni, S. M. and Shah, S. P. (1998). Response of reinforced concrete beams at high strain rates, *ACI Structural Journal*, 95:6,705-715.

Mutsuyoshi, H. and Machida, A.(1984). Dynamic properties of reinforced concrete piers, *Proceeding of eighth world conference on earthquake engineering*, San Francisco, 299-306.

Shah, S.P., Wang, M.L.and Chung, L. (1987). Model concrete beam-column joints subjected to cyclic loading at two rates, *Materials and Structures*, 20:2, 85-95.