Experiment of Reinforce Concrete Beams at Different Loading Rates

Shiyun Xiao, Wenbo Cao & Haohao Pan
Dalian University of Technology, Dalian 116024, China

SUMMARY: (10 pt)
Dynamic experiment of reinforced concrete (RC) beams at different loading rates was carried out with the MTS electro-hydraulic servo system to study the effect of loading rates on the mechanical behaviours of RC beams. The monotonic displacement control loading with loading rates 0.1mm/s, 0.5mm/s, 1mm/s, 5mm/s and10mm/s was imposed. According to the test results, the effect of loading rates on the failure shape and loading-displacement curve of RC beams was investigated. The effects of loading rates on the cracking, ultimate and failure strengths and displacements, ductility and dissipated energy capability of RC beams were studied. The conclusions could be drawn: with the increasing of loading rates, firstly, the cracks distributed more equably but their depth decreased. Secondly, the cracking, ultimate, failure strengths and displacements of RC beams increased with the loading rates. Finally, the ductility and dissipated energy capability of RC beams improved obviously with the increasing loading rates.

Keywords: reinforced concrete (RC) beam; loading rate; bearing capacity; ductility; dissipated energy capacity

1 INTRODUCTION

The dynamic characteristics of reinforced concrete (RC) members, such as RC beams and RC columns, are inevitably affected by loading rates. On the one hand, concrete and steel are the typical rate-dependent materials: their strengths, stiffness and brittleness (or ductility) are affected by loading rates. The acceptable conclusion was that the dynamic tensile and compressive strengths and the elastic modulus of concrete increased with the increasing loading rate. The yield strength and the corresponding strain of steel increased with the increasing loading rate but the elastic modulus was rate-independent. On the other hand, the failure configuration of RC members due to the dynamic loading was different from that due to the static loading. Except the familiar flexural failure, the brittle shear failure may be occurred on some circumstances though the RC members were designed according to the flexural failure, viz, the shear failure occurred before the flexural failure. This phenomenon has been confirmed by the dynamic test of RC members (Ghabossi, 1984; Krauthammer, 1984; Krauthammer, 1986).

Recently, more and more researchers had paid attention to study the effect of strain rates on RC members. A survey of the behavior of reinforced concrete subjected to dynamic loading was presented and the response of reinforced concrete materials and elements to different strain rates was reviewed and discussed (Fu, 1991). Of all the RC members, the RC beam was studied intensively. Krauthammer (1984) presented a method for the analysis of reinforced concrete (RC) box-type structures under the effects of severe dynamic loading conditions and Krauthammer (1986) demonstrated it by employing it for the analysis of seven different events and the evaluated it's accuracy by comparing numerical and experimental results. And then, the dynamic responses of RC beams under the dynamic loading condition were farther studied with the rate-dependent model and compared with the rate-independent model (Beshara 1992; Al-Haddad 1995; Farag 1996; Kulkarni 1998). Kunnath (1990) presents an efficient model for inelastic biaxial bending interaction of reinforced concrete sections and the validity of the proposed scheme was demonstrated through the analytical simulation of available biaxial experiments on reinforced concrete columns and comparison with other analytical models. Sziveri (1999) presented a parallel scheme for the time marching procedure using the explicit Newmark's algorithm to improve the computational efficiency of the transient dynamic non-linear analysis of reinforced concrete plates subjected to blast or seismic loading. Taking the Timoshenko beam and the buried frame structure for example, Fang (1997; 2001) studied the effects of the strain rate on the defence structures. Wang (2006) did a time-frequency analysis of the displacement responses from the impact excitation vibration test on a reinforced concrete beam to study the relationship between the nonlinear dynamic characteristics of reinforced concrete beam and its impairing degree. These studies indicated that the effects of loading rates on the dynamic behaviours of RC members are not negligible. But, only few design codes take into account the effects of loading rates on the RC structures because the study on the effects of loading rates are not enough and the results are still not accepted by most engineers.

In this paper, the dynamic experiment of five reinforced concrete beams at different loading rates was carried out to study the effect of loading rates on the mechanical behaviours of RC beams. According to the test results, the effect of loading rates on the failure shape and loading-displacement curve of RC beams was investigated. The cracking, ultimate and failure strengths and displacements, ductility and dissipated energy capability of RC beams were studied.

2 EXPERIMENTAL INVESTIGATION

2.1 Beam design and material properties

The testing RC beam was designed based on the consideration of the fundamental period of the beam consisting with that of general concrete buildings. The RC beam with dimensions 1400 mm in length, 150 mm in width and 200 mm in depth was simply supported within 1200 mm span as shown in Figure 1. The micro-stone commercial concrete, the average compressive strength of which was 25.42MPa, was adopted and its grade was C25. Two steel bars with 10mm in diameter were horizontally placed in the top and bottom of the beam respectively. The distributed steel tie was 6mm in diameter and 150mm in distributed distance. The design strength of reinforcing steel of the RC beam was 320MPa. Figure 1 also showed the steel bar distribution of the beam.

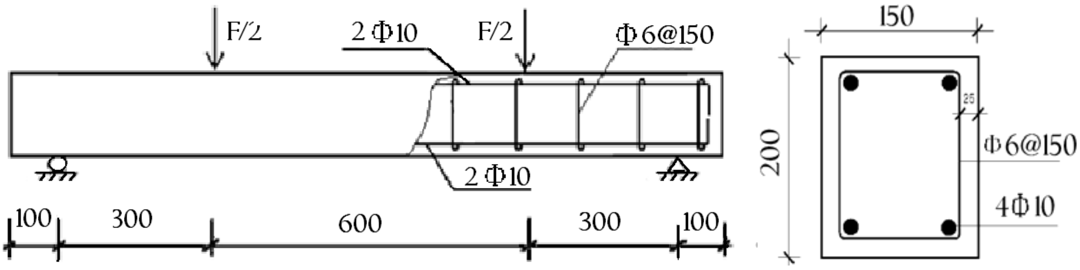


Figure 1. Loading and reinforcement layout of RC beam

2.2 Loading setup

The test was carried out on the structural laboratory in Shenyang Jianzhu University. The multi-channel MTS servo-hydraulic loading system was adopted for the loading equipment. The maximal thrust loading is up to 350kN, the maximal push loading is up to 240kN and the maximal displacement is up to 500mm. The stiffness of the supporting structure of the testing beam must be large enough to reduce the measurement error. In order to avoid the local failure of concrete, two 20mm width armor plates were imbedded into the bottom and the top of the RC beam to support the beam and the loading steel beam respectively. The setup and the loading equipment are shown in

Figure 2. In order to study the effect of loading rates on the dynamic behaviours of RC beam, the displacement loadings with different loading rates, such as 0.1mm/s, 0.5mm/s, 1mm/s, 5mm/s and 10mm/s, were imposed on five beams BM-1, BM-2, BM-3, BM-4 and BM-5, respectively.

Figure 2. Test setup and loading equipment

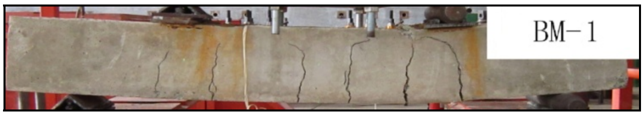
2.3 Measure setup

Because the maximum loading rate was up to 10 mm/s, a high-speed data acquisition system was needed to avoid the loss of test data. The dynamic data acquisition system DH5937 produced by Donghua Test Technology Co., Ltd. was adopted in this experiment. The system could collect various electrical signals and the maximum acquisition frequency could achieve 20 kHz. All 8 channels could work at the same time and the simultaneous collection frequency of every channel would achieve 2.5 kHz. In order to collect enough but not too much data, different collection frequencies were adopted at different loading rates in this test. The collection frequencies of five test beams BM-1, BM-2, BM-3, BM-4 and BM-5 were 20Hz, 50Hz, 200Hz, 1000Hz and 2000Hz, respectively. In this experiment, the strain of reinforcements, the mid-span displacement of the beam and the MTS loading actuator were acquired.

3 EXPERIMENTAL RESULTS

3.1 Failure analysis of RC beams

In this experiment, the effect of loading rates on the dynamic behaviors of the pure bending segment was studied mainly. The failure configurations of five RC beams at different loading rates are shown in Figure 3. The failure configurations were the same at different loading rates and the vertical cracks, which were located on the bottom of the beam, were caused by the tensile failed concrete. By careful observation and comparison, the width of the crack decreased with the increasing loading rates and they distributed more uniform. The reason may be that the rapid loading rate delayed the propagation of internal micro-cracks and enlarged the crack field, which caused the developments of the external cracks. So, more visible cracks appeared and the width of the cracks decreased with the increasing loading rates.



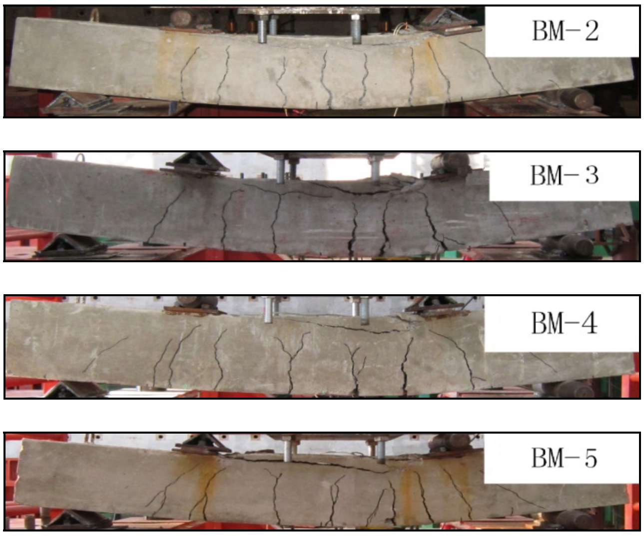


Figure 3. Failure mode of beams at different loading rates

3.2 Influence of loading rates on the loading-displacement curves

The mid-span loading-displacement curve was the important factor to evaluate the mechanical behaviors of the simply supported RC beam. Figure 4 illustrated the five mid-span loading-displacement curves of the RC beam at different loading rates.

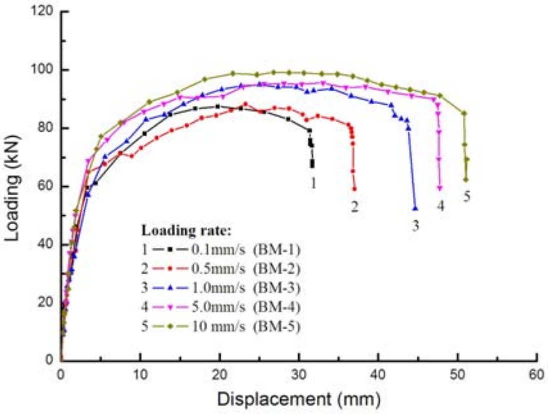


Figure 4. The mid-span loading-displacement curves at different loading rates

From this figure, the loading-displacement curve was linear at the load beginning and became nonlinear slowly with the increasing load because the stiffness of the RC beam decreased, which caused by the failure tensile concrete. Further increasing the load, the bottom crack zone of the RC beam enlarged and the nonlinear behavior of the loading-displacement curve became more obviously. When the bottom steel yielded, the stiffness of the RC beam decreased rapidly and the loading-displacement curve turned flatter obviously. Further increasing the load again, the top compressive concrete was crushed and the RC beam should achieve the ultimate state, and then the mid-span displacement increased rapidly but the loading decreased little. The RC beam should be destroyed till the bottom steels were snapped.

Compared the five curves, it was concluded that, at the load beginning, the reinforced steel and concrete were within their elastic stages and the loading-displacement curve appeared as the line, and the effect of the loading rates was neglectable. With the increasing loading rate, the strain rate effects of the concrete and steel appears more obvious and the loading-displacement curve appeared as the nonlinear arity. So, the yield loading, the ultimate loading, the yield displacement and the ultimate displacement increased distinctly.

3.3 Influence of loading rates on the crack, critical and failure loading

Table 1 listed the crack loading, the ultimate loading and the failure loading, in which the failure loading was selected as 85 percent of the ultimate loading in this paper. From the figure, it was clear that the crack loading, the ultimate loading and the failure loading increased with the increasing loading rate. Compared with the beam BM-1, the crack loading of the beam BM-2, BM-3, BM-4 and BM-5 increased 4.78 percent, 6.70 percent, 13.77 percent and 14.09 percent, respectively. Similarly, the ultimate loading and the failure loading of the beam BM-2, BM-3, BM-4 and BM-5 increased 0.95 percent, 8.54 percent, 9.23 percent and 13.36 percent, respectively.

Table 1 The Crack loading, ultimate loading and failure load of beams

Number	BM-1	BM-2	BM-3	BM-4	BM-5
Cracking loading	24.48	25.65	26.12	27.85	27.93
Ultimate loading	87.51	88.34	94.98	95.59	99.2
Failure loading	74.38	75.09	80.73	81.52	84.32

According to the references, the increases in strengths followed a linear-logarithmic relationship with the increases in the loading rate. Similarly, Figure 5 illustrated the relationship between the crack loading and the ultimate loading and the logarithmic of the loading rate. It was concluded that the yield loading, the ultimate loading, the yield loading and the ultimate loading increased distinctly. Compared with the crack loading and the ultimate loading, the lineal rule of the crack loading was more obvious than that of the ultimate loading. The reason was that the effect of the loading rate on the concrete was more significant than that on the steel. The concrete carried most of the loading before the crack of the concrete, so the effect of the loading rate on the crack loading was more closed to that on the concrete. On the ultimate state, most of the tensile loading on the bottom of the beam was carried by the tensile steel but most of the compressive loading on the top of the beam was carried by the compressive concrete, so the effect of the loading rate on the ultimate loading of the RC beam was determined by the effect combination of the loading rate on the concrete and steel. The effect combination was weak than the effect on the crack loading of the RC beam and more easy to be influenced by other factors. So the test results about the effect of the loading rate on the ultimate loading were discrete, just shown in Figure 5.

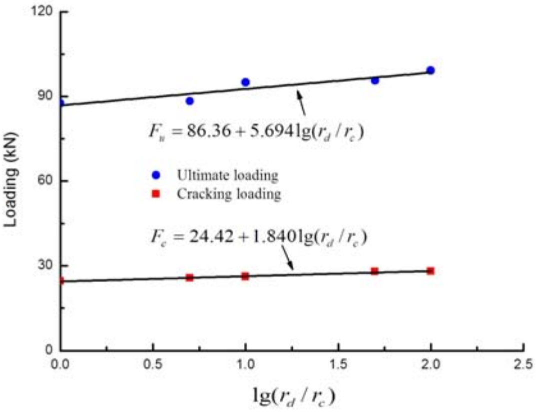


Figure 5. The relationship between the loading and the logarithmic of the loading rate

3.4 Influence of loading rates on the deformation behaviour

The ductility was the important factor to evaluate the aseismic behaviour of the RC beam. The ductility coefficient was defined by the ratio of the deformation on the failure state to that on the yield state in this paper, as follow:

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y}$$

where, Δ_y is the mid-span displacement of the RC beam on the yield state and Δ_u is that on the failure state.

The mid-span crack displacement, the yield displacement, the ultimate displacement and the ductility coefficient were listed in Table 2. It was also concluded that the mid-span crack displacement, the yield displacement, the ultimate displacement and the ductility coefficient of the RC beam increased obviously with the increasing loading rate. Compared with the beam BM-1, the mid-span crack displacement of the beam BM-2, BM-3, BM-4 and BM-5 increased 5.1 percent, 16.9 percent, 25.4 percent and 32.2 percent, respectively. Similarly, the mid-span yield displacement of the beam BM-2, BM-3, BM-4 and BM-5 increased 3.5 percent, 11.2 percent, 17.1 percent and 19.1 percent, the mid-span ultimate displacement increased 17.2 percent, 39.4 percent, 51.6 percent and 57.9 percent and the ductility coefficient increased 13.2 percent, 25.4 percent, 29.4 percent and 32.5 percent, respectively. These test results were agreed with the previous test of reinforced concrete members (Li, 2010). The enhancement in the strength of concrete with the increasing strain rate was obviously greater than that of the steel. So, the compressive height of concrete on the yield state decreased with the increasing loading rate, which caused the decreasing curvature of the RC beam. But, on the ultimate state, the compressive height of concrete increased and caused the increasing mid-span curvature and the enhancement of the ductile coefficient of the RC beam with the increasing loading rate.

Table 2 Displacement (mm) and ductility coefficient of beams

Beam Number	BM-1	BM-2	BM-3	BM-4	BM-5
Cracking displacement	0.59	0.62	0.69	0.74	0.78
Yield displacement	3.4	3.52	3.78	3.98	4.05
Ultimate displacement	31.41	36.81	43.8	47.61	49.59
Ductility coefficient	9.24	10.46	11.59	11.96	12.24

3.5 Influence of loading rates on the bending moment curvature curves

The mid-span bending moment-curvature curves of the RC beam at different loading rates were depicted in Figure 6. It was clear that the bending moment-curvature curves were same as the loading displacement curves because the dimension and the mechanical parameters of five RC beams were the same. So, the evolvement rule and the effect of loading rates on these curves were same.

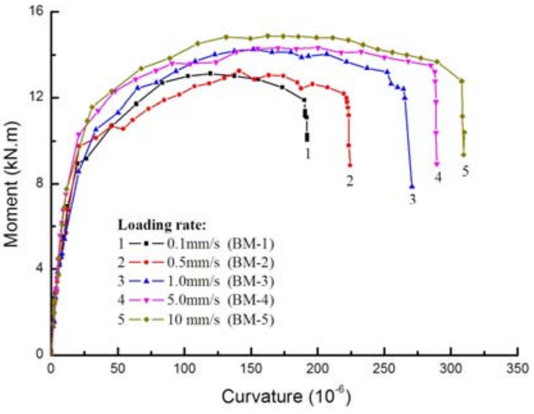


Figure 6. The mid-span bending moment-curvature curves at different loading rates

The crack curvature, the ultimate curve and the failure curvature were listed in Table 3. The mid-span bending moment and curvature increased obviously with the increasing loading rate and the effect of loading rates on these was same as that on the loading the displacement of the RC beam.

Table 3 The moment and curvature of beams at different status

Number	Crack		Ultimate		Failure	
	Moment	curvature	Moment	curvature	Moment	curvature
BM-1	3.67	3.5	13.13	119.5	11.16	190.4
BM-2	3.85	3.8	13.25	149.0	11.26	223.1
BM-3	3.92	4.2	14.25	152.1	12.11	265.5
BM-4	4.18	4.5	14.39	155.2	12.19	288.5
BM-5	4.20	4.7	14.88	159.4	12.65	300.5

3.6 Influence of loading rates on the energy dissipation capacity

The energy dissipation capacity of the RC beam was defined by the capacity to absorb the energy dissipated by concrete and reinforcing steel at one loading process. The energy dissipation capacity was obtained by calculating the area between the loading curve and the transverse axis. Generally, energy dissipation capacity depends on various parameters such as reinforcement ratio, arrangement of reinforcing bars, and shape and size of the members' cross-sections. The energy dissipation of the RC beam at different loading rates was listed in Table 4. It was clear that the energy dissipation capacity increased dramatically with the increasing loading rate. Compared with the beam BM-1, the energy dissipation capacity of the beam BM-2, BM-3, BM-4 and BM-5 increased 17.01 percent, 53.94 percent, 72.20 percent and 90.04 percent, respectively. The enhancement of the energy dissipation capacity was because that the increasing loading rate not only increased the crack, ultimate and failure carrying capacity of the RC beam, but also improved the deformation ability.

Table 4 Dissipated energy of RC beams

Number	BM-1	BM-2	BM-3	BM-4	BM-5
Dissipated energy (kN.m)	2.41	2.82	3.71	4.15	4.58

4 CONCLUSION

Some conclusions could be drawn from the test results of five RC beams at different loading rates:

(1) The failure configurations of five RC beams were the same at different loading rates and the width of the crack decreased with the increasing loading rates and they distributed more uniform.

(2) The yield loading, the ultimate loading, the yield displacement and the ultimate displacement of RC beams increased distinctly with the increasing loading rate.

(3) The crack loading, the ultimate loading and the failure loading increased with the increasing loading rate and the crack loading and the ultimate loading and the logarithmic of the loading rate followed linear.

(4) The energy dissipation capacity of RC beams increased dramatically with the increasing loading rate.

ACKNOWLEDGEMENT

This study was founded by the National Science Foundation of China under grant No. 51178082 and No. 51121005.

REFERENCES

Al-Haddad, M.S. (1995). Curvature ductility of reinforced concrete beams under low and high strain rates. *ACI Structural Journal* **92:5**, 526-534.

Beshara, F.B.A. and Virdi, K.S. (1992). Prediction of dynamic response of blast-loaded reinforced concrete structures. *Computers and Structures* **44:1**, 297-313.

Fang, Q., and Qian, Q.H. (1997). Discussion on the consideration of the ratesensitivity in design of protective structures. *Explosion and Shock Waves* **17(2)**: 104-110. (In Chinese)

Fang, Q., Liu, J.C., Zhang, Y.D. and Qian, Q.H. (2001). Finite element analysis of failure modes of blast-loaded r/c beams. *Engineering Mechanics* **18:2**, 1-8. (In Chinese)

Farag, H.M. and Leach, P. (1996). Material modelling for transient dynamic analysis of reinforced concrete structures. *International Journal for Numerical Methods in Engineering* **39:12**, 2111-2129.

Fu, H.C., Erki, M.A. and Seckin, M. (1991). Review of effects of loading rate on reinforced concrete. *Journal of Structural Engineering* **117 :12**, 3660-3679.

Ghabossi, M.W.A. and Isenberg, J. (1984). R/C Structures Under impulsive Loading. *Journal of Structural Engineering* **110:3**, 505-522.

Krauthammer, T. (1984). Shallow-Buried RC Box-Type structures. *Journal of Structural Engineering* **110:3**, 637-651.

Krauthammer, T., Bazeos, N., and Holmquist, T.J. (1986). Modified SDOF Analysis of RC Box-Type Structures. *Journal of Structural Engineering* **112:4**, 726-744.

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

Kunnath, S.K. and Reinhorn, A.M. (1990). Model for inelastic biaxial bending interaction of reinforced concrete beam-columns. *ACI Structural Journal* **87:3**, 284-291.

Li, M. and Li, H.N. (2010). Dynamic test and constitutive model for reinforcing steel. *China Civil Engineering Journal* **43:4**, 70-75. (In Chinese)

Sziveri, J., Topping, B.H.V. and Ivanyi, P. (1999). Parallel transient dynamic non-linear analysis of reinforced concrete plates. *Advances in Engineering Software* **30:9**, 867-882.

Wang, L.H., Zhou, X.Y., Yan, W.M. and Yu, M. (2006). Test Study on the Nonlinear Dynamic Characteristics of Reinforced Concrete Beams. *Journal of Seismological Research* **29:1**, 65-71. (In Chinese)