Journal of Science and Technology in Civil Engineering, NUCE 2021. 15 (3): 136–143

EFFECT OF LOADING RATE ON FLEXURAL BEHAVIOR OF CONCRETE AND REINFORCED CONCRETE BEAMS

Nguyen Trung Hieu[a,*], Nguyen Van Tuan[b]

[a]*Faculty of Building and Industrial Construction, National University of Civil Engineering, 55 Giai Phong road, Hai Ba Trung district, Hanoi, Vietnam*
[b]*Faculty of Building materials, National University of Civil Engineering, 55 Giai Phong road, Hai Ba Trung district, Hanoi, Vietnam*

Article history:
Received 13/07/2021, Revised 01/08/2021, Accepted 02/08/2021

Abstract

The elasto-plastic characteristics of plain concrete are inevitably affected by the loading rate. This paper presents an experimental investigation on the effect of loading rate on flexural behavior of concrete and reinforced concrete (RC) beams, which was carried out with Walter+bai electro-hydraulic servo system. Three-point bending tests on $100 \times 100 \times 400$ mm prismatic concrete samples and $80 \times 120 \times 1100$ mm RC beams with different displacement controlled loading rates of 0.01 mm/min, 0.1 mm/min, and 3 mm/min were imposed. Based on the test results, the effects of loading rates on the load-displacement curve, cracking, and ultimate load-carrying capacities of RC beams were evaluated.

Keywords: loading rate; reinforced concrete beam; cracking; strength; deflection.

https://doi.org/10.31814/stce.nuce2021-15(3)-11

1. Introduction

Reinforced concrete (RC) structures may be subjected to various types of loads during their life. In addition to the frequent effects of service loads, RC structures can be subjected to dynamic loads such as earthquakes, blasts, or impact. As illustrated in Fig. 1, when an RC frame is subjected to the sudden removal of a supporting due to blast or impact, the RC beams just above the removed column may be subjected to a concentrated load at a very high loading rate. The effect of this load can be considered as an impact load.

The experimental evaluation of the dynamic behavior of RC members such as RC beams and RC columns is inevitably affected by the testing loading rate. This loading rate-dependent behavior directly impacts the properties, i.e. strengths, stiffness, and brittleness (or ductility), of typical building materials such as concrete and steel. The general observation is that the increasing loading rate can enhance the tensile and compressive strengths, the elastic modulus of concrete [1, 2]. For steel reinforcement, its yield strength and the corresponding strain increase proportionally to the loading rate, but the elastic modulus exhibits a rate-dependent behavior [3–7]. According to the experimental results obtained by Ghabossi et al. [7], Krauthammer et al. [8], the failure mode of RC beams caused by dynamic load was different from that of static load. The brittle shear failure may have occurred in some circumstances, even though RC beams were designed for flexural failure. The loading rate and

*Corresponding author. *E-mail address:* hieunt@nuce.edu.vn (Hieu, N. T.)

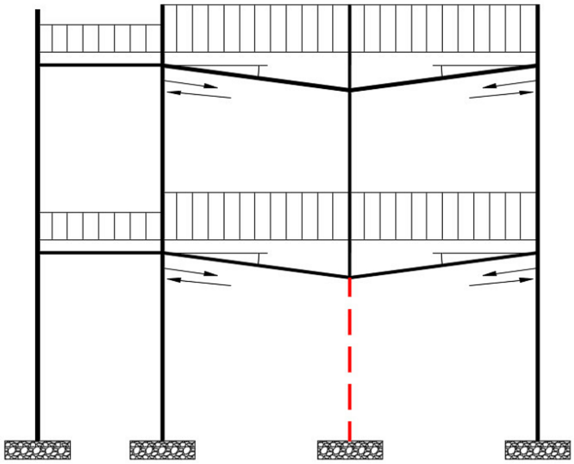

Figure 1. Concentrated load suddenly acting on RC beam after a sudden removal of a supporting column

the loading rate sensitivity of concrete and steel reinforcing bars would be the main reasons for this change in the failure mode.

Many researchers have widely studied the effect of loading rates on the behavior of concrete and RC structures. Kraunthammer [9] presented a method for analyzing RC box-type structures under severe dynamic loading conditions. Besides, the dynamic responses of RC structures under the dynamic loading condition were further studied and compared with the rate-dependent model [3, 4, 10]. In 2008, Cotsovos et al. [11] conducted the numerical investigation into the dynamic response of RC beams subjected to the transverse loading with a high loading rate. Vaz et al. [12] studied the flexural behavior of strengthened RC beams under cyclic loading. Xiao et al. [13], Miyauchi [14] studied the effect of the loading rate on cyclic behavior of RC beams and the obtained results show that the dissipated energy capacity of RC beams obviously increased with increasing loading. This phenomenon is because increasing the loading rate increases the cracking, yielding, and ultimate strengths of the RC beams and improves the deformation ability.

The above-mentioned studies indicate the strong influence of loading rate on the behavior of RC structures. Understanding the behavior of RC structures under different loading rates will be the basis for ensuring the sustainability of the RC structures, however, only a few design codes consider the effect of loading rate on the RC structures. In Vietnam, experimental studies on the behavior of RC structures in different working states such as flexural and compression have attracted interest from many researchers [15–17]. However, the loading rate on the experimental structure has not been clearly stated in these experimental studies.

This paper presents an experimental investigation on the effect of loading rate on the flexural behavior of RC beams under monotonic loading at different loading rates.

2. Experimental investigation

An experimental program based on a three-point bending test was conducted at three different loading rates of 0.1 mm/min, 1.0 mm/min, and 3.0 mm/min to study the effect of loading rates on prismatic concrete samples and reinforced concrete beam samples. These values were selected corresponding to three levels of loading rates, i.e. slow, medium and high, following the specification of the loading rate of introducing a compressive load into the concrete sample, which is given in Vietnamese standard TCVN 3118:1993 [18], and suitable for the existing equipment capacity.

2.1. Test specimens and material properties

The effect of loading rates on flexural behavior of concrete and RC beams was evaluated using an experimental design as follows:

- A total of 9 prismatic concrete samples with a size of 100 × 100 × 400 mm were divided into three groups (03 samples/group) corresponding to 03 loading rates mentioned above, denoted as M_1, M_2, and M_3.

- A total of 06 RC beams with a cross-section size of 80 × 120 mm, and a length of 1100 mm were divided into three groups (02 beams/group) corresponding to 03 loading rates, denoted as D_1, D_2, and D_3.

The test specimen series and applied loading rates are given in Table 1.

Table 1. Summary of the experimental sample series and applied loading rates

Sample	Notation	Number of samples	Loading rate (mm/min)
Prismatic concrete specimens	M_1	03	0.1
	M_2	03	1.0
	M_3	03	3.0
RC beams	D_1	02	0.1
	D_2	02	1.0
	D_3	02	3.0

Fig. 2 shows the dimensions and details of reinforcement of the RC beam specimens. The reinforcing bars were selected based on the calculation according to the guidelines of the Vietnamese standard TCVN 5574:2018 [19]. Six beam specimens were geometrically identical with a length of 1100 mm, a depth of 140 mm, and a width of 80 mm and were cast using the same batch of concrete. All beams had two longitudinal reinforcing steel bars of 8 mm in diameter (2∅8) at the tensile side and two bars with a diameter of 6 mm (2∅6) at the compression side. The transverse reinforcement was 4 mm in diameter, which was arranged with a space of 50 mm in the shear span. Yield strengths of reinforcing bars with diameters of ∅6 and ∅8 are 310 MPa and 330 MPa, respectively.

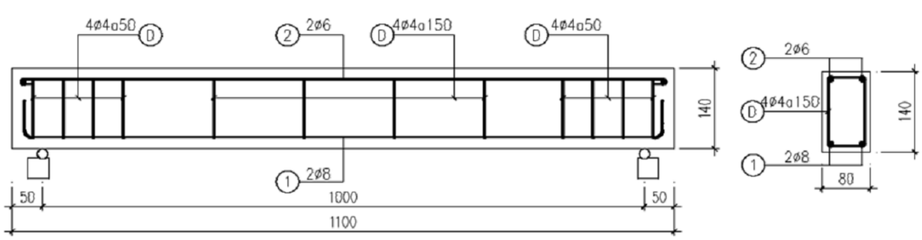

Figure 2. Dimensions, reinforcement details of RC beams

The concrete mix proportions used in this study are given in Table 2. The 28 day-compressive strength of concrete was determined through the 150 × 300 mm cylinder specimens. The average cylinder strength is also presented in Table 2.

Table 2. Concrete mix proportion (unit kg/m^3)

Cement PCB30 (kg)	Sand (kg)	Crushed stone 10-20 mm (kg)	Water (kg)	The 28-day compressive strength (MPa)
390	680	1210	185	31.5

2.2. *Test setup*

Figs. 3 and 4 show the typical test setup of prismatic concrete specimens and RC beam specimens, respectively. All specimens were tested according to a simply supported beam, subjected to three-point bending, and the load was applied in a displacement control mode. At the loading position, the mid-span displacement of the test specimens was determined using one Linear Variable Differential Transducers (LVDT). All test data, including the applied load and vertical displacement, were automatically recorded with a data logger unit of the testing machine. The experiments on prismatic concrete and RC beam specimens were carried out with 03 loading rates, as given in Table 1.

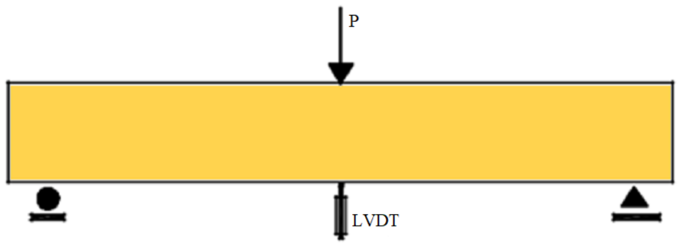

Figure 3. Scheme diagram of the three-point bending test

(a) Prismatic concrete specimens

(b) RC beams

Figure 4. Test setup

3. Experimental results and discussions

3.1. *Effect of loading rate on flexural behavior of concrete*

Fig. 5 shows the load-displacement relationship of test samples at 03 different loading rates. Each value is presented as the average of 03 sample test results. The values of the ultimate load causing damage to the sample and the corresponding displacement at failure are given in Table 3.

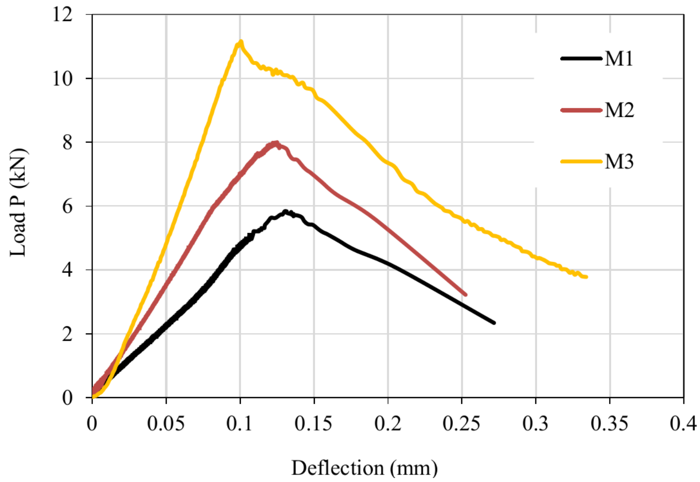

Figure 5. The load-displacement relationship of prismatic concrete specimens

Table 3. Load and displacement values at failure

Loading rate (mm/min)	0.1	1	3
The ultimate load P_{ul} (kN)	5.84	8.0	11.16
The corresponding displacement f_{ul} (mm)	0.131	0.125	0.100

The obtained results clearly show the influence of the loading rate on the flexural behavior of concrete. It can be seen that the failure load Pul increases proportionally to the loading rate. Compared with the result of the sample at the loading rate of 0.1 mm/min, the failure load increases 37% and 91% at the corresponding loading rates of 1 mm/min and 3 mm/min. Additionally, it can be observed that for the maximum displacement at the time of failure of the test specimens ful, the displacement of the specimen decreases with an increase in the loading rate. For example, the displacement at the loading rates of 1 mm/min and 3 mm/min decreases 4.6% and 23.7% compared with that at a loading rate of 1 mm/min.

Based on the results in Fig. 5, the elastic modulus of the test sample can be calculated from the load-displacement relationship in the range of (0.2 - 0.5) P_{ul}. Note that the slope of the load-displacement curve increases proportionally to the loading rate. The above analysis reveals that increasing the loading rate gives a significant increase in strength but reduces the deformation capacity of concrete. The following experimental investigation on the RC beams will evaluate the influence of the mechanical properties of concrete on the performance of the RC structures.

3.2. *Effect of loading rate on flexural behavior of RC beams*

Fig. 6 shows the load-displacement relationship of the tested RC beams. From the obtained results, it can be observed that when changing the loading rate, the behavior of RC beams could be divided into the following three stages:

- The OA stage (precracking stage) shows a linear load-displacement relationship. Point A represents the moment value corresponding to a change in the slope of the load-displacement relationship curve or the change in the stiffness of the RC beam. In this stage, cracks appear on the concrete in the tensile zone and allow determining the load causing the beam cracking, denoted as P_{cr}.

- The AB stage (cracking stage) shows the development of the crack. Point B corresponds to the second slope change of the load-displacement relationship that associates with the time once the reinforcement begins to yield. At this time, it is possible to determine the load causing plastic failure of the RC beam, denoted as P_{yl}.

- The BC stage (failure stage): After yielding the reinforcement, the bearing capacity of the beam is influenced by its compression zone. It can be observed that the load increases in this stage are small. Point C corresponds to when the concrete in the compression zone is broken, and the test beams are entirely damaged. The corresponding moment allows determining the ultimate load acting on the RC beam, denoted as P_{ul}.

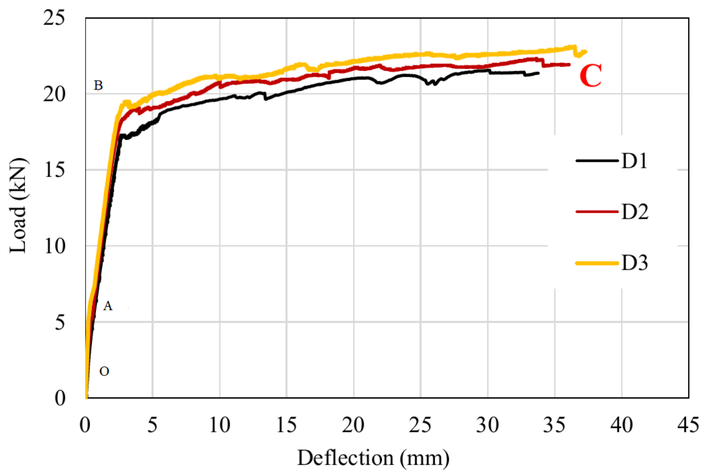

Figure 6. The load-displacement relationship of RC beams

Characteristic values for the flexural behavior of the RC beams such as P_{cr}, P_{yl}, P_{ul} and corresponding displacements are presented in Table 4, in which each value is presented an average of 02 beam test results.

Table 4. Characteristic values and corresponding displacements of RC beams

Loading rate (mm/min)	0.1	1.0	3.0
Cracking load, P_{cr} (kN)	2.25	3.81	4.70
Yielding load, P_{yl} (kN)	17.90	18.55	19.9
Ultimate load, P_{ul} (kN)	21.77	22.51	23.97
Deflection at a first crack, f_{cr} (mm)	0.26	0.25	0.24
Yielding deflection, f_{yl} (mm)	2.82	2.80	2.87
Ultimate deflection, f_{ul} (mm)	34.92	36.88	37.05

The results from Table 4 show that the load values acting on the RC beam specimens are directly related to the mechanical characteristics of the concrete, such as the cracking load P_{cr} (depending on the tensile strength of the concrete). The load-bearing capacity of concrete in the compression zone (determined by the difference between the ultimate load and the yielding load, P_{ul} - P_{yl}) increases proportionally with the increase in the loading rate. These results are complete with those obtained from the test on the prismatic concrete sample presented in Section 3.1 that the flexural strength of the concrete increases with the loading rate.

Fig. 7 shows photos of the failure modes of test beams when changing the loading rate regarding the failure mechanism of the test specimens. It can be seen that the testing beams failed in flexure. At a loading speed of 0.1 mm/min, multi-cracks appeared in fairly uniform distribution. The higher the loading rate, the fewer the number of cracks and the more concentrated at the position of the applied load. The crack width also has a similar behavior. Thus, when the loading rate is increased, the distribution of the load on the structure away from the load application area is slow, and less than the bearing participation of the structure area is mobilized away from this load application area. The higher the loading rate increases, the higher the tendency of local failure in the loading area is.

(a) 0.1 mm/min

(b) 1.0 mm/min

(c) 3.0 mm/min

Figure 7. The failure modes of RC beams at different loading rates

Table 5. The bearing participation of concrete in the compression zone

Loading rate (mm/min)	0.1	1.0	3.0
P_{ul} - P_{yl} (kN)	2.25	3.81	4.70

4. Conclusions

The results obtained from this study demonstrate the influence of loading rate on the flexural behavior of RC beams. Based on the obtained results, the following main conclusions are drawn:

- The strength of concrete increases with the rate of loading. Therefore, in the experimental work, the loading rate should be limited to accurately evaluate the performance of test structures.

- For the flexural test on RC beams, the cracking, the yielding load, and the ultimate load increase with an increase in the loading rate.

- When the loading rate increases, the test structures tend to fail in the local mode. The overall structural capacity could not be reached, especially the mobilization of the structural capacity away from the position of the load point.

References

[1] Fu, H. C., Erki, M. A., Seckin, M. (1991). Review of Effects of Loading Rate on Concrete in Compression. *Journal of Structural Engineering*, 117(12):3645–3659.

[2] Bischoff, P. H., Perry, S. H. (1991). Compressive behaviour of concrete at high strain rates. *Materials and Structures*, 24(6):425–450.

[3] Fu, H. C., Erki, M. A., Seckin, M. (1991). Review of Effects of Loading Rate on Reinforced Concrete. *Journal of Structural Engineering*, 117(12):3660–3679.

[4] Abbas, A. A., Pullen, A. D., Cotsovos, D. M. (2010). Structural response of RC wide beams under low-rate and impact loading. *Magazine of Concrete Research*, 62(10):723–740.

[5] Adhikary, S. D., Li, B., Fujikake, K. (2012). Dynamic behavior of reinforced concrete beams under varying rates of concentrated loading. *International Journal of Impact Engineering*, 47:24–38.

[6] Al-Haddad, M. S. (1995). Curvature Ductility of RC Beams Under Low and High Strain Rates. *ACI Structural Journal*, 92(5):526–534.

[7] Ghaboussi, J., Millavec, W. A., Isenberg, J. (1984). R/C Structures Under Impulsive Loading. *Journal of Structural Engineering*, 110(3):505–522.

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

[9] Krauthammer, T. (1984). Shallow-Buried RC Box-Type Structures. *Journal of Structural Engineering*, 110(3):637–651.

[10] Kulkarni, S. M., Shah, S. P. (1998). Response of Reinforced Concrete Beams at High Strain Rates. *ACI Structural Journal*, 95(6):705–715.

[11] Cotsovos, D. M., Stathopoulos, N. D., Zeris, C. A. (2008). Behavior of RC Beams Subjected to High Rates of Concentrated Loading. *Journal of Structural Engineering*, 134(12):1839–1851.

[12] Vaz, A. P. R., Shehata, I. A. E. M., da Conceição Domingues Shehata, L., Gomes, R. B. (2013). Behaviour of RC beams strengthened by partial jacketing under cyclic loading. *Materials and Structures*, 47(3):383–396.

[13] Xiao, S., Li, J., Mo, Y.-L. (2018). Effect of loading rate on cyclic behavior of reinforced concrete beams. *Advances in Structural Engineering*, 21(7):990–1001.

[14] Miyauchi, K. (1997). Damage Evaluation of RC Beams under Reversed Cyclic Loading Based on Dissipated Energy of Perfectly Elasto-Plastic Body. *Concrete Research and Technology*, 8(2):19–29.

[15] Quynh, D. D., Hieu, N. T., Dat, P. X., Hung, N. M. (2021). Experimental study on flexural behavior of RC beams strengthened with CFRP composite sheets under sustaining load. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 15(2V):1–11. (in Vietnamese).

[16] Chinh, N. V. (2021). Flexural performance of reinforced concrete beams made with locally sourced fly ash. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 15(2):38–50.

[17] Dat, P. X., Vu, N. A. (2020). An experimental study on the structural performance of reinforced concrete low-rise building columns subjected to axial loading. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 14(1):103–111.

[18] TCVN 3118:1993. *Heavyweight concrete - Method for determination of compressive strength*. Vietnamese Standard.

[19] TCVN 5574:2018. *Design of concrete and reinforced concrete structures*. Vietnamese Standard.