Review

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Experimental, Theoretical and Numerical Research Progress on Dynamic Behaviors of RC Structural Members

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Experimental, Theoretical and Numerical Research Progress on Dynamic Behaviors of RC Structural Members

Rouhan Li [1], Mao Gao [1], Hongnan Li [2], Chao Li [2,*] and Debin Wang [3]

[1] College of Transportation Engineering, Department of Civil Engineering, Dalian Maritime University, Dalian 116026, Liaoning, China; lirouhan@dlmu.edu.cn (R.H. Li); gm1222@dlmu.edu.cn (M. Gao)
[2] Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China; hnli@dlut.edu.cn (H.N. Li)
[3] School of Civil Engineering, Dalian Jiaotong University, Dalian 116028, Liaoning, China; wdb1215@163.com (D.B. Wang)
* Correspondence: Correspondence: chaoli@dlut.edu.cn (C. Li)

Abstract: In this paper, the research progress on dynamic behaviors of RC structural members is reviewed from experimental, theoretical and numerical perspectives. Firstly, the basic overview, measurement methods, main conclusions and current limitations of available dynamic loading tests are presented. Then the theoretical studies on the dynamic constitutive models of RC materials, the dynamic increase factor (DIF) model for concrete and reinforcing steel and the proposed modified models of dynamic behavior parameter at the structural member level are summarized. Finally, the available modelling approach and the method for incorporating the dynamic effect in numerical simulation of RC structures are reviewed. Moreover, a brief introduction is made to the dynamic hysteretic model established on the experimental data, which provides an alternative approach to consider the dynamic effect beside the commonly used DIF method. This paper provides valuable reference for experimental studies and numerical simulations on the dynamic behaviors of RC structures, and also puts forward some issues that need to be solved in the future research works.

Keywords: reinforced concrete members; dynamic effect; experimental test; dynamic modified model; numerical modelling

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1. Introduction

Reinforced concrete (RC) structure is one of the most widely used building constructions in current civil engineering field. In addition to static loads, RC structures may also be subjected to different types of dynamic loads during their service life, such as explosion, impact, earthquake and wind load, etc. In the past decades, a large number of RC structures have been damaged or even collapsed in the seismic hazards. The seriously damage phenomena of RC structures subjected to real earthquake load are shown in Figure 1. In order to reduce the large human and economic losses caused by seismic damage, on one hand, the seismic performance of RC structures needs to be continually enhanced at the design stage; and on the other hand, to provide a guideline for structural operation and maintenance stages, it is required to accurately evaluate the mechanical behaviors of RC structures under earthquake load.

(**a**) Chile earthquake (**b**) Yushu earthquake

Figure 1. Damage phenomena of RC structures under real earthquake load.

It has been widely accepted that reinforcement and concrete exhibit different mechanical properties under static and dynamic loading, namely the strain rate sensitivity of materials [1]. The consistent research findings are concluded that as the loading rate increases, both the tensile strength and compressive strength of concrete, the yield strength and ultimate strength of reinforcement are magnified, and the elastic modulus and the strain corresponding to the compressive strength of concrete are also affected by the loading rate [2]. As for structural members consisting of RC materials, such as columns [3–6], beams [7–14], shear walls [15–19] and joints [20–25], changes in mechanical behaviors to different degrees are observed for specimens under various loading rates, namely the dynamic effect at the member level. Different failure patterns of RC structural members could be observed in seismic hazards, as shown in Figure 2. In the past half century, a number of dynamic loading tests have been carried out for better understanding the mechanical behaviors of RC structural members subjected to dynamic (i.e. blast, impact and seismic) loading rates. However, the current seismic codes and most of the structural seismic analysis do not specially consider the strain rate sensitivity of RC materials. The application of dynamic increase factor (DIF) for modifying the mechanical properties of RC materials suggested by the CEB-FIP Model Code [26] and some other scholars [27–29] provides a common approach for considering the dynamic effect. Nevertheless, it should be mentioned that there is still a lack of deep understanding on the mechanism for explaining the macro mechanical behaviors of RC structural members under dynamic loads.

(**a**) Damage of joint elements (**b**) Damage of column elements

(**c**) Damage of wall elements (**d**) Damage of beam elements

Figure 2. Damage patterns of RC structural members in seismic hazards.

In this paper, the existing research works are systematically summarized from experimental, theoretical and numerical aspects, and the directions of future effort are also prospected. This review paper provides a significant reference for seismic design and analysis works aiming at improving the seismic performance of RC structures.

2. Experimental studies on dynamic behaviors of RC structural members

2.1. Overview of dynamic loading tests on structural members

In civil engineering field, several methods for testing dynamic behaviors of RC structural members have been adopted by scholars, including the pseudo-static test, the pseudo-dynamic test, the shaking table test and the earthquake observation test [2]. Among these test methods, the pseudo-static test method is mostly used. By employing the monotonic or cyclic loading scheme, the dynamic behaviors of RC structural members from the elastic stage, the plastic stage to the final failure stage can be obtained. However, the shortage of this method lies in that it could not reasonably reflect the influences of strain rate or loading rate on the mechanical behaviors of RC structural members. As for the dynamic test methods, the shaking table test method can provide the most accurate and reliable results for evaluating the dynamic response and failure mechanism of structural members and systems under earthquake excitations, but it requires a large amount of time and financial effort. In the earthquake observation test, seismic instruments need to be installed on the onsite building to measure the structural dynamic response under real earthquake. By contrast, the pseudo-dynamic test method is more preferably used to acquire the seismic action of structures by using the controlling approach though computational analysis [30].

At present, most of the available tests on RC structural members are carried out under static loading rate. In recent years, with the development of experimental technique and the improvement of empirical knowledge, a number of dynamic loading tests have been performed on different RC structural members. Figure 3 shows the strain rate range for RC structures under different loads. It is noted that the most significant difference between the dynamic loading tests ($10^{-4}/\text{s} < \dot{\varepsilon} < 10^{1}/\text{s}$) and the pseudo-static loading tests ($10^{-6}/\text{s} < \dot{\varepsilon} < 10^{-5}/\text{s}$) is the magnitude of strain or loading rate exerted on the specimens.

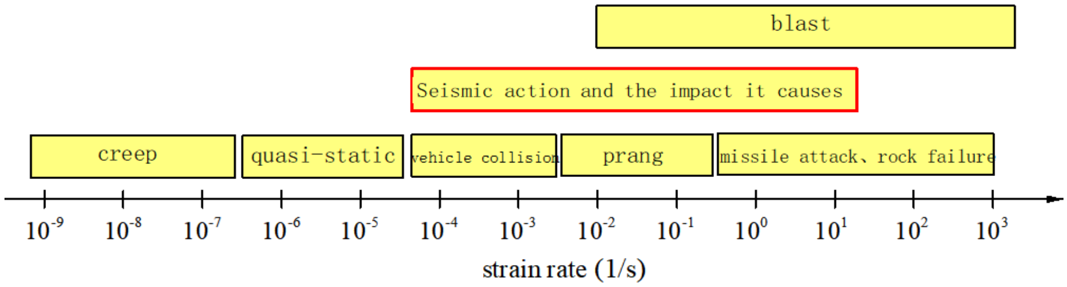

Figure 3. Strain rate range for RC structure under different dynamic loadings [31].

As the earthquake is a kind of dynamic load, the dynamic loading tests provide results more close to the real seismic behaviors of RC structural members. Table 1 summarizes the basic information on available dynamic loading tests (i.e. member type, specimen number, loading rate and scheme) of RC structural members tested under the seismic strain rate.

Table 1. Summary of dynamic loading tests on RC structural members.

No.	Reference	Type	Number	Loading rate	Loading scheme
1	Bertero et al[32]	Beam	6	0.1、10/s	Mono, cycl
2	Shah et al [33]	Joint	3	2.5×10^{-3}-1.0Hz	Cycl
3	Chung and Shah[20]	Joint	12	0.0025-2.0Hz	Cycl
4	Kulkarni and Shah[34]	Beam	14	0.0071-380mm/s	Mono
5	Gutierrez et al[35]	Column	3	0.02-1Hz	Cycl
6	Orozco[36]	Column	3	0.22-1m/s	Cycl
7	Bousias et al[37]	Column	12	/	Cycl, Biax
8	Gibson et al[38]	Joint	4	0-405mm/s	Cycl
9	White et al[39]	Beam	4	0.0167-36mm/s	Mono, Cycl
10	Li et al[40]	Column	30	0.000011-0.0167/s	Mono
11	Zhang et al[41]	Beam	36	1.05×10^{-5}、1.25×10^{-3}/s	Mono
12	Fukuda et al[42]	Beam	48	4×10^{-4}-2m/s	Mono
13	Witarto et al[5]	Column	4	0.05-5Hz	Cycl
14	Adhikary et al [7,9,14]	Beam	24	4×10^{-4}-2m/s	Mono
15	Adhikary et al[43]	Beam	30	0-5.6m/s	Mono
16	Perry et al[44]	Column	4	0.7×10^{-4}-0.7×10^{-3}/s	Mono, Cycl
17	Marder et al[12]	Beam	17	100Hz	Mono, Cycl
18	Yan[45]	Beam	/	1×10^{-5}-1×10^{-3}/s	Cycl
19	Yan[45]	Column	/	10^{-5}-10^{-2}/s	Mono
20	Xiao et al[46]	Beam	5	0.1-10mm/s	Mono
21	Pan[23]	Joint	10	0.1-10mm/s	Cycl
22	Zou et al[47]	Column	/	10^{-5}-10^{-2}/s	Mono
23	Fan et al[22]	Joint	3	0.4-40mm/s	Cycl
24	Wang et al[21]	Joint	8	0.4-40mm/s	Cycl
25	Zhang[16]	Shear wall	7	10^{-5}-10^{-3}/s	Cycl
26	Yuan and Yi[48]		18	3.5×10^{-4}--1m/s	Mono
27	Li and Li[10]	Beam	16	0.05-30mm/s	Mono, Cycl
28	Wang et al[49]	Column	30	0.1-50mm/s	Mono, Cycl, Biax
29	Jiang[50]	Column	12	0.1-20mm/s	Mono, Cycl, Biax
30	Zeng[51]	Beam	6	10^{-2}/s-8.85m/s	Mono
31	Xu et al[15]	Shear wall	2	1-10mm/s	Cycl

32	Song et al[4]	Beam	5	3.5-6 m/s	Mono
33	Ye et al[52]	Beam	14	0.8m/s	Mono
34	Zhou et al[53]	Beam	7	0.06mm -66mm /s	Mono
35	Xiang et al[54]	Beam	7	/	Mono
36	Feng et al[55]	Beam	10	3-7.7m/s	Mono
37	Mutsuyoushi and Machida[56]	Beam	14	0.1、10、100cm/s	Mono, Cycl
38	Otani et al[57]	Beam	8	0.1、100mm/s	Cycl
39	Fujikake[13]	Beam	6	5×10^{-4}m/s、2m/s	Mono
40	Ghannoum et al[30]	Column	10	0.25mm/s-1061mm/s	Cycl

Note: No information is provided in the original literature, which is represented by "/" in the table; 'Mono' and 'Cycl' denote the monotonic and the cyclic loading scheme, respectively; 'Biax' denotes the specimen is loaded in two horizontal directions, and the default in table is in single horizontal direction.

From the summarized results, it can be seen that as compared with the static loading tests, the number of dynamic loading tests is relatively less, and beam and column members are mostly investigated [4,7,30,33,35,56]. It is noted that the majority of tests were conducted on the electro-hydraulic servo loading system, a few were carried out by using the drop-hammer impact testing machine. As earthquake load is multidimensional in nature, it is more reasonable to experimentally study the seismic performance of RC members and structures in space [8]. Wang et al. [49] studied the multidimensional dynamic behaviors of RC columns by using two horizontal and one vertical electro-hydraulic servo actuators. Due to the difficulty of multi-axis loading test of RC members and higher requirements for test equipment, the available literature and experimental data of multi-axis dynamic loading tests are relatively inadequate[37,50].

2.2. Measurement methods for dynamic loading test

In dynamic loading tests, the observed quantities that the researchers are focused on include the bearing capacity, displacement, strain, failure mode and crack that can be directly measured or observed; and the stiffness, ductility, damage and energy dissipation capacity that need to be acquired indirectly. In the following sections, the measurement of test data are summarized in details. Figure 4 shows the main measured quantities of RC structural members in the dynamic loading tests.

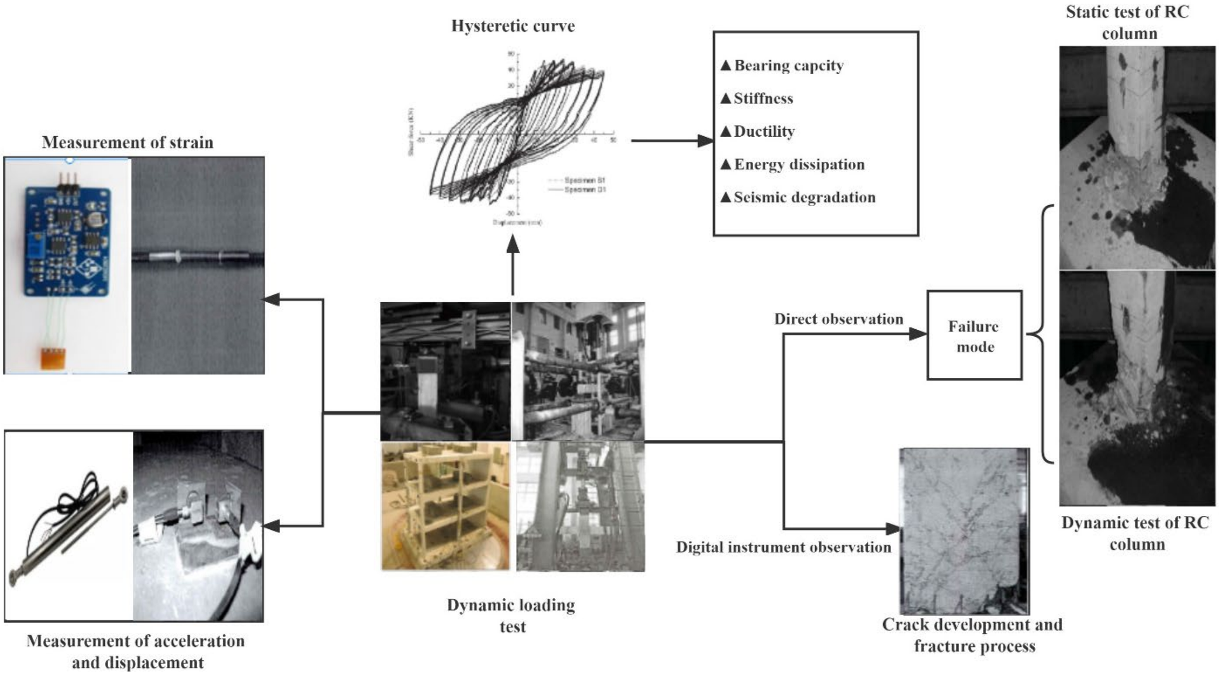

Figure 4. Measured quantities of RC structural members in dynamic loading test.

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For measuring the force-displacement relationship of RC structural members, mechanical sensors inside or out of the loading device have been commonly used to collect the test data. For example, Wang et al. [49] used the force sensor and displacement sensor of the servo hydraulic actuator to measure the horizontal top displacement and bottom reaction force of the column specimens. Gutierrez et al. [35] used the mechanical sensor installed in series with the piston rod of the servo device to measure the force, and used LVDT sensor to collect the displacement. In the dynamic loading test performed by Shunsuke et al. [57], the laser displacement sensor was used to measure the lateral displacement, and the strain gauge was used to measure the deformation at plastic hinge region.

For measuring the material strain in RC members, strain gauges are generally pasted on the surface of structural members or on the reinforcement inside the members (Kenneth et al. [6], Wang [58], Long [59], Adhikary et al. [7]). Zhang [60] used the fiber Bragg grating strain sensor to measure the concrete strain for further deriving the real-time strain rate during the whole loading process, and the acceleration sensor was employed for measuring the horizontal and vertical acceleration of floors. Perry et al. [44] installed LVDT sensors between the two frames of servo hydraulic testing machine to measure the longitudinal strain of columns members.

It is noticed that a few novel methods have been adopted by researchers to measure the displacement of RC structural members. For example, Liu [61] used planar truss of LVDT sensors arranged outside the column specimen to measure the displacement. By using geometrical transformation, the flexural, shear and bond-slip deformation components of column specimens were indirectly determined. However, to the best of authors' knowledge, few research works have been reported on the change in deformation components of RC structural members under dynamic loading rates. Zhang [16] arranged force and displacement meters at the four corners as well as the bottom of the shear wall specimens for measuring the displacement and shear deformation of the specimens under dynamic loading rates.

In general, the failure modes and crack patterns of RC structural members can be directly observed with naked eyes [5,32,36,58]. Moreover, for a few dynamic loading test that the crack development was not feasibly measure, the high performance measuring equipment has been employed by researchers as alternatives. For example, Adhikary et al. [43] used digital photography and high-speed camera to capture the crack development and fracture process of RC beams under the drop hammer impact test. Similar approach has been adopted by Ye. et al [52]for investigating the failure pattern and crack development of RC column members under impact loading.

Besides the above physical quantities that can be measured directly, damage and energy dissipation capacity are generally obtained using indirect methods. In most of the available dynamic tests, the hysteretic curve of force-displacement can be acquired by measuring the bearing capacity and displacement of structural members in the process of cyclic loading; and the degradation of bearing capacity and stiffness, the seismic damage and the energy dissipation capacity can be further derived by analyzing the test data of hysteretic loops[3,20,33,57]. By using the self-developed carbon nanofiber aggregate (CNFA) as an internal sensor, which could well capture the transient changes of structural force and stiffness with almost no time delay, WITARTO et al. [5] detected the seismic damage of RC column specimens under various loading rates.

2.3. Summary of experimental findings

As both concrete and reinforcing steel are rate-sensitivity materials, their tensile and compressive mechanical properties are closely relevant to loading rate. Consequently, the mechanical behaviors of RC structural members under different loading rates are not the same, which have been demonstrated by a large number of experiments. Bertero et al. [32] experimentally studied the mechanical behaviors of RC simply supported beams under high loading rate. It was found that with the increase of loading rate, the yielding bearing capacity of members was increased, whereas the ultimate bearing capacity did not change significantly; the strain rate had minor influence on the energy dissipation capacity, and the members at higher loading rate was more likely to transform into brittle shear failure mode. Mutsuyoushi and Machida [56] found in their experiments that with the increase of loading rate, the failure of RC members tended to change from flexural failure to shear failure. Kulkarni and shah [34] carried out dynamic tests on RC simply supported beams at different loading rates. As the loading rate increased, the failure mode of some specimens changed from shear to bending failure, which was contrary to the conclusions obtained by most researchers. Shah et al. [33] conducted cyclic loading tests of beam-column joints under different strain rates. It was observed that with the increase of loading rate, the number of cracks became less, while the damage was intensified and the plastic deformation was increased.

Furthermore, available dynamic loading tests have also shown that mechanical properties of components under different loading rates are closely related to structural parameters. Chung and Shah [20] carried out experimental studies on cantilever beam members at different loading rates considering the effects of shear-span ratio and longitudinal reinforcement ratio. It was found that the bearing capacity is increased, while the cracks decreased and ductility is decreased for specimens at higher loading rate, and the strain rate effect was more significant for specimens with lower reinforcement ratio. Li et al. [40] studied the mechanical behaviors of RC column members with different longitudinal reinforcement, transverse stirrup and cross section shape under uniaxial dynamic loading. It was observed that with the increase of loading rate, the dynamic effect became less unobvious for specimens with higher strength degrade of concrete, while the influence of cross-sectional shape was little. Zhang et al. [41] conducted an experimental study on the fracture behavior of RC beams under different strain rates considering the size effect of specimens, and the experimental results showed that strain rate sensitivity of specimens increased with the increase of specimen size. Fukuda et al. [42] conducted dynamic tests on 48 RC beams with varied shear-span ratio and reinforcement ratio under different loading rates. It was found that the influence of loading rate on the ultimate bearing capacity of specimens is more significant for shear failure specimens than for flexural failure specimens. Adhikary et al. [7,9,14] carried out tests on a large number of RC beams at different loading rates, and the following conclusions were obtained: the dynamic effect becomes more obviously with the decrease of longitudinal reinforcement ratio or the increase of shear span ratio. A large number of dynamic tests have been carried out on reinforced concrete beams and columns by the authors [3,10,49,62,63]. It was concluded that the increase of material strength and stirrup ratio will lead to the decrease of dynamic effect. Moreover, the strain rate sensitivity of the monotonic loading member is more significant than that of the cyclic loading member, and the area of concrete crushing and falling off and reinforcement buckling is more localized.

2.4. Discussion on dynamic loading tests

According to the available dynamic loading tests, the following consistent conclusions can be obtained: With the increase of loading rate, the bearing capacity, stiffness and energy dissipation capacity of members are enhanced, the ductility might be reduced, and the degradation of stiffness and bearing capacity are aggravated. However, the existing research works still have the following shortcomings: (1) in most of the dynamic loading tests, specimens were tested under un-axial loading. Therefore, in order to more accurately reveal the dynamic behaviors of RC structural members, it is required to further carry out experimental studies under multidimensional loading condition; (2) currently, the main physical quantities measured in dynamic loading tests are stress, strain, displacement and force, and there is a lack of experimental study on the influence of dynamic effect on the deformation and failure mechanism of structural members; (3) due to the dynamic loading tests are inadequate as compared to the traditional static loading tests, thus in-depth research works are still needed to investigate the influence law of dynamic effect on the seismic behaviors of structural members with various structural parameters.

3. Theoretical studies on dynamic behaviors of RC structural members

3.1. Dynamic modified model at material level

The influences of loading rate on the mechanical properties of concrete [64–71] [72–78] and reinforcing steel [27,79–83] have been investigated by a large number of experimental studies. The rate-sensitivity of concrete material is influenced by many factors, including (1) the internal causes, such as the dispersion in material properties, the humidity [84–87] and the temperature [88,89], etc. (2) the exterior causes, such as the test loading method[90,91], the equipment instability and the measurement error, etc. By collecting test data of concrete under a wide range of loading rate (Figure 5), Pajak [90] found that the ratio of dynamic compressive strength to the corresponding static strength can reach 3.5, whereas the dynamic tensile strength to the corresponding static strength can reach 13. Moreover, it was pointed out by Bischoff [92] that the ratio of strain at the dynamic compressive strength to the corresponding static strain is in the range of 70%～140%.

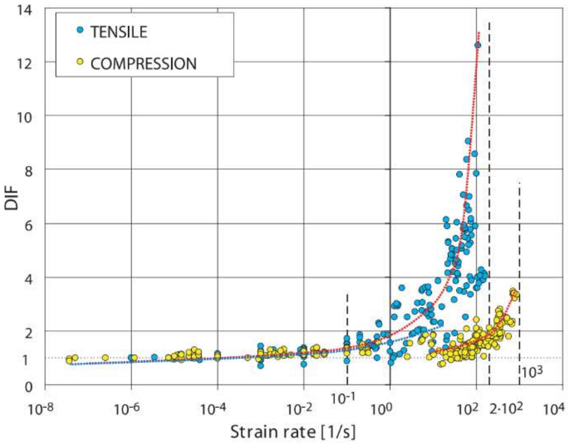


Figure 5. Statistical diagram of dynamic increase factor (DIF) for concrete tensile and compressive strength with variation in strain rate [90].

As a multiphase composite material, the constitutive relationship of concrete is highly complex. Based on different theoretical backgrounds, i.e. the visco-elastic theory, visco-plastic theory, damage mechanics theory and fracture mechanics theory, a variety of dynamic concrete constitutive models have been established [93–99]. To reflect the influences of loading rate on the mechanical properties of concrete (e.g. the enhancement of compressive and tensile strength [100], the more brittle behavior for the descending branch of stress-strain curve [90]), the dynamic increase factor (DIF), which is defined as the ratio of the mechanical behavior parameter of concrete under dynamic loading to the corresponding value under static loading has been the most widely used. Figure * shows the statistic results of change in dynamic increase factor (DIF) of concrete with strain rate from different research works [90]. It is noted that a few researchers have removed the lateral inertia force and the end friction force of concrete specimens for obtaining the DIF models [101,102]. Table 2 summarized the commonly used model of dynamic increase factor (DIF) for concrete.

Table 2. Commonly used model of dynamic increase factor (DIF) for concrete.

Model	Range of dynamic strain rate	quasi-static strain rate	Type of formula	Modified parameters
CEB Model [26]	3.0×10^{-5}/s~300/s	3.0×10^{-5}/s (compression) 3.0×10^{-6}/s (tension)	Exponential	f_{cd} E_{cd} ε_{cfd} f_{td} E_{td}
Malvar model [103]	10^{-6}/s~160/s	1.0×10^{-6}/s	Exponential	f_{td}
Tedesco and Ross Model [104]	10^{-7}/s~10^{2}/s	10^{-7}/s	Linear logarithmic	f_{cd} f_{td}
Yan Model [69]	10^{-5}/s~10^{-2}/s	10^{-5}/s	Linear logarithmic	f_{cd} E_{cd} f_{td} E_{td}
Xiao and Zhang Model [105]	10^{-5}/s~10^{-1}/s	10^{-5}/s	Linear logarithmic	f_{cd} ε_{cfd}
Li Model [28]	10^{-5}/s~10^{-2}/s	10^{-5}/s	Linear logarithmic	f_{cd}

Note: The values of quasi-static strain rate $\dot{\varepsilon}_0$ for compressive and tensile parameters are the same if no otherwise specified. The modified parameters f_{cd} and f_{td} denote the dynamic compressive and tensile strength of concrete; E_{cd} and E_{td} denote the elastic modulus of concrete under dynamic compressive and tensile loading conditions; ε_{cfd} denote the dynamic strain corresponding to the ultimate compressive strength of concrete.

To reflect the enhancement of yielding and ultimate strength under dynamic loading rate, researchers have established various dynamic constitutive models for reinforcing steel. For example, Johnson and Cook [106] developed the dynamic constitutive model of reinforcement considering the combined influences of strain rate c effect and temperature. Morquio et al. [107] developed the predicted model for mechanical properties of reinforcement considering the strain rate-sensitivity and the size effect. Based on the thermo-visco-plastic theory, a dynamic constitutive model of reinforcement applicable for a wide range of loading rate was proposed by Rodríguez-Martínez [108]. Compared with the above models, the DIF models based on the dynamic loading experimental results are more widely employed. Table 3 summarized the commonly used model of dynamic increase factor (DIF) for reinforcing steel.

Table 3. Commonly used model of dynamic increase factor (DIF) for reinforcing steel.

Model	Range of dynamic strain rate	quasi-static strain rate	Type of formula	Modified parameters
CEB Model [26]	5.0×10^{-5}/s~10/s	5.0×10^{-5}/s	Linear logarithmic	f_{yd} f_{ud} f_{nd}
Malvar model [103]	10^{-4}/s~10/s	3.0×10^{-4}/s	Exponential	f_{yd} f_{ud}
Lin Feng Model [27]	<2/s	3.0×10^{-4}/s	Linear logarithmic	f_{yd} f_{ud}
Li and Li Model [83]	2.5×10^{-4}/s~0.1/s	2.5×10^{-4}/s 10^{-5}/s	Linear logarithmic	f_{yd} f_{ud} ε_{hd}

Note: The modified parameters f_{yd}, f_{ud} and f_{nd} denote the dynamic yielding, ultimate and breaking strength of reinforcing steel; ε_{hd} denotes the dynamic strain at initial point of strain hardening stage.

From Tables 3 and 4, it can be seen that the DIF models consider a variety of material strength degrade and a wide range of loading rate. The mechanical behavior parameters for dynamic modification include the compressive strength (f_{cd}), tensile strength (f_{td}), elastic modulus of concrete (E_{cd} and E_{td}), and the yielding strength (f_{yd}) and ultimate strength (f_{ud}) of reinforcing steel. Generally, the exponential or linear logarithmic expressions are used for calibrating the DIF formulas. By modifying the quasi-static behavior parameters of material using the DIF models, the dynamic behavior parameters of material are obtained, which can be used for establishing the dynamic constitutive models. More importantly, the dynamic modified models at material level can be further utilized to consider the influences of dynamic effect on the RC structural members.

Table 4. Dynamic modified model for mechanical behavior parameters of RC structural members.

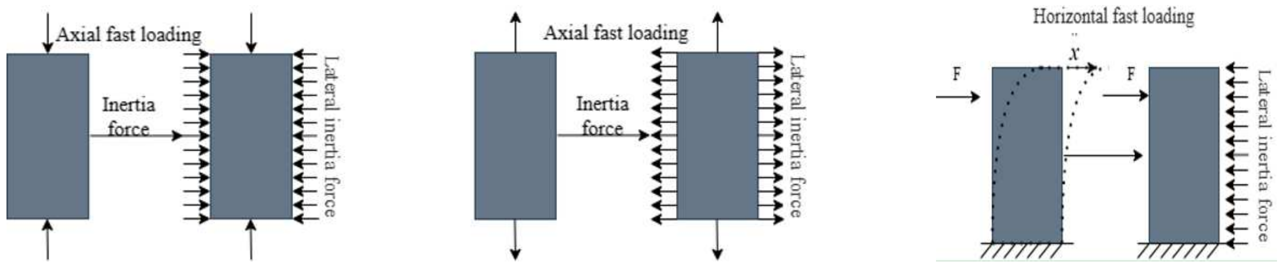
Reference	Equations of dynamic modified model	Model type
Adhikary et al. [7]	Maximum resistance of RC regular beams (1) With transverse reinforcements $DIF=\left[1.89-0.067\rho_g-0.42\rho_v-0.14(a/d)\right]e^{\left[-0.35-0.052_{\rho_g}+0.179_{\rho_v}+0.18(a/d)\right]\delta}$ (2) Without transverse reinforcements $DIF=\left[0.004\rho_g+0.136(a/d)-0.34\right]\log_e\delta+\left[0.009_{\rho_g}+0.41(a/d)+0.157\right]$	FE simulation results-based (Deterministic)
Adhikary et al. [14]	Maximum resistance of RC deep beams $DIF=\left[1.25-0.04\rho_g-0.13\rho_v+0.05(\frac{a}{d})\right]e^{\left[0.22-0.03\rho_g-0.17\rho_v+0.03(a/d)\right]\delta}$	FE simulation results-based (Deterministic)

	RC beams without transverse reinforcements $DIF=\left[0.45+0.09+0.48(\frac{a}{d})\right]e^{\left[0.30-0.05\rho_g-0.05(a/d)\right]\delta}$	
Wang [58]	Ultimate bearing capacity of RC columns (1) Different axial load ratio $DIF=1.0+c_n\lg\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\quad c_n=0.1426n^2-0.0614n+0.0337$ (2) Different concrete strength conditions $DIF=1.0+c_f\lg\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\quad c_f=1\times10^{-4}f_c^2-0.068f_c+0.153$ (3) Different longitudinal reinforcement ratios $DIF=1.0+c_\rho\lg\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\quad c_\rho=0.0129\rho^2-0.0643\rho+0.1182$	FE simulation results-based (Deterministic)
Li et al. [111]	Mechanical behavior parameters of RC columns (including yielding and ultimate bearing capacity, effective stiffness and ductility coefficient) $DMC_j\left(\mathbf{x},\mathbf{\Theta}\right)=\sum_{i=1}^{6}\theta_i h_i\left(\mathbf{x}\right)+\sigma\varepsilon$ $=\theta_1 f_y/f_c'+\theta_2 n_0+\theta_3\lambda+\theta_4\rho_l+\theta_5\rho_s+\theta_6\lg\left(\dot{\varepsilon}_d/\dot{\varepsilon}_0\right)+\sigma\varepsilon$	Experimental date-based (Probabilistic)
Fan [112]	Shear bearing capacity of RC joints $DIF=0.99679+0.1536n+0.02326\lg\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$	Experimental date-based (Deterministic)

Note: the meaning of symbols in the each dynamic modified model can be referred from the relevant references.

3.2. Dynamic modified model at member level

Consensus has been reached among scholars on the influences of loading rate on the mechanical behaviors of RC structural members. However, few research works have been focused on the mechanism of the dynamic effect exhibited in the experimental tests. It could be explained from different perspectives: (1) Strain rate-sensitivity of materials, i.e. the physical mechanism of rate-sensitive concrete is attributed to the viscosity effect of the cement matrix [90]; (2) Inertial effect of member (Figure 6): based on the kinetic theory, the structural inertial force is magnified with the increase of loading rate, and the constraint of interior material is also intensified, thus resulting in the enhancement of macro bearing capacity and stiffness of structural members [109]. (3) Evolution of micro-crack: due to the limitation of time and space at higher loading rate, the probability that transfer of internal force in structural member and occurrence of bond-slip between concrete and reinforcement through more stronger regions is increased [90].



(a) axial compression (b) axial tension (c) horizontal load

Figure 6. Schematic diagram of inertial effect for RC structural members under dynamic loading.

Due to the non-negligible dynamic effect on the mechanical behaviors of RC structural members, scholars have made attempts to establish dynamic modified models for considering the dynamic effect at the member level. Zhan et al. [110] developed the dynamic modified model for predicting the maximum and residual deflection of RC beam members based on a large amount of experimental data. Adhikary et al. [7] developed dynamic modified model for evaluating the ultimate bearing capacity for RC beam members based on a large number of numerical simulation results by utilizing the LS-DYNA software, and further studied the influences of longitudinal reinforcement ratio and transverse stirrup ratio on the dynamic modified factor of RC beam members. By using the dynamic modified material constitutive model, Wang et al. [58]established finite element model of RC column members with the OpenSees software. Accordingly, the expressions of DIF (i.e. the ratio of dynamic mechanical behavior parameter to the corresponding static parameters at the member level) for ultimate bearing capacity of columns considering the axial load ratio, concrete strength and longitudinal reinforcement ratio are obtained., Fan et al. [22] derived the calculation equations for shear strength of concrete and developed the modified model for predicting the dynamic shear bearing capacity of RC joints through multiple linear regression analysis of test data, considering the influences of dynamic effect and axial force. Based on the dynamic loading test database of RC column members and the Bayesian update theory, Li et al. [111] proposed the probabilistic model of DMC (Dynamic modified coefficient) for evaluating the yielding and ultimate bearing capacity, the effective stiffness and the displacement ductility ratio for RC column members under dynamic loading. The proposed modified models can accurately and reliably predict the mechanical behaviors of column members at seismic loading rate. Table 4 lists some of the representative dynamic modified models for RC structural members developed on the finite element (FE) simulation or the experimental results.

3.3. Discussion on dynamic modified models

To accurately evaluating the dynamic behaviors of RC structural members, quite a large number of research works have been focused on the establishment of dynamic constitutive models and DIF models of concrete and reinforcing steel materials, and the development of dynamic modified models at the member level. Strictly speaking, these studies were mostly carried out in half theoretical and half empirical way, and cannot be separated from the experimental tests. The drawbacks of available research works include (1) currently, the most commonly used method for considering the dynamic effect of RC structural members is to modify the static constitutive model parameters using the DIF models at the material level. However, whether the dynamic modification at material level can effectively reflect the dynamic effect on the mechanical behaviors of structural members still needs to be further verified; (2) the usage of dynamic modified models proposed at the member level provide a direct and efficient approach to reflect the influences of dynamic effect on the mechanical behaviors of RC structural members. Due to the inadequate test data, the suitability and accuracy of models need to be improved; (3) the mechanism of dynamic effect on the mechanical behaviors of structural members is an unsolved problem, which needs to be thoroughly investigated.

4. Numerical studies on dynamic behaviors of RC structural members

4.1. Overview of numerical studies considering dynamic effect

Up to now, the dynamic behaviors of RC structural members and structures have been numerically investigated considering the dynamic effect by many researchers. The merits of the numerical simulation over the experimental test lie in that it not only needs relatively less human and material resources, and it can also be repeatable and applied to broader range of structural parameters and loading rates. The computational accuracy and reliability of the numerical results are directly dependent on the methods adopted for simulating the structural dynamic behaviors.

Two methods are currently available for considering the dynamic effect in numerical simulation of RC structures, i.e. the dynamic constitutive model (DCM) method and the dynamic increase factor (DIF) method [113]. The DCM method requires tedious and time-consuming computation, thus it is less adopted in engineering practice and research works. On the contrary, the DIF method has been more commonly adopted by researchers. Quite a few studies have been performed by using this method to investigate the influences of dynamic effect on the seismic behaviors of RC members and structures [114–119]. The disadvantages of the DIF method are concluded as follows [113]: (1) It cannot fully reflect the adverse effects of dynamic effect on the structural displacement ductility and performance degradation; (2) The influence of dynamic effect on the shear and bond-slip behaviors of RC structural members is generally neglected.

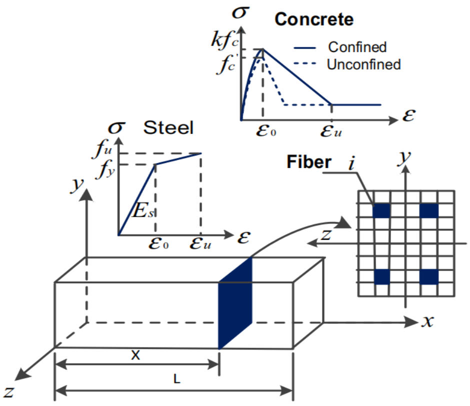
Moreover, due to the randomness in the structural members (e.g. geometric sizes, material properties, reinforcement conditions) and the external dynamic load, a few attempts have been tried to consider the dynamic effect in a probabilistic manner [120]. Simplified or alternative method for considering strain rate in materials have been proposed by researchers [121–123]. Through the numerical simulations, the effectiveness and reliability of the proposed numerical models and methods have been validated with test data, and the influences of dynamic effect on the seismic behaviors of RC members and structures have been more comprehensively investigated.

4.2. Numerical model for simulating structural dynamic behaviors

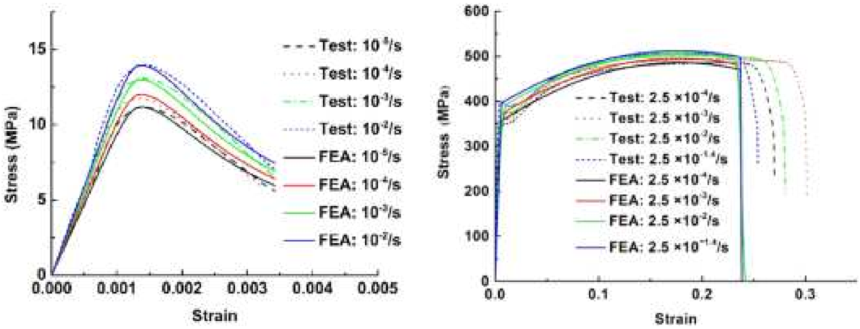
4.2.1. Finite element model considering dynamic effect

For developing reasonable FE models for RC structural members, different material and element types and modelling techniques have been adopted by researchers based on the available FE software or the self-compiled programs. Based on the ABAQUS software, the detached model of RC column members was established by one of the authors [58] using the solid element and the truss element respectively to simulate concrete and reinforcing steel. The dynamic effect was included by modifying static material parameters in the damage plastic model of concrete and the ideal elastoplastic model of reinforcement with the corresponding DIF models [26,27]. For simplicity, the measured strain of longitudinal reinforcement at the bottom was used to derive the strain rate of the whole column member.

Wang et al. [124] developed the user material subroutine for concrete and reinforcement considering the strain rate effect of materials. It is suitable for the three-dimensional fiber beam element on the ABAQUS software and can be further applied to the nonlinear dynamic analysis and the progressive collapse assessment of RC and steel structures. On the basis of this research work, the model was refined by Liu et al. [125] through incorporating the strength and stiffness deterioration induced by the accumulated damage of material, which has been demonstrated to provide better simulation results on the dynamic behaviors of RC beams and column members. The effectiveness of the subroutine and the proposed beam-column element (Figure 7(a)) has also been verified by Zhang et al. [119] in numerically simulating the dynamic response of a shaking table test frame structure. The DIFs of micro-concrete and iron wire developed on the test data (Figure 7(b)) were used to represent the material dynamic properties in the beam-column models.



(**a**) The proposed fiber beam-column element



(**b**) Stress-strain curves of micro-concrete and iron wire at different strain rates

Figure 7. Schematic plot of dynamic fiber model for RC beam-column members employing the user material subroutine [119].

Based on the LS-DYNA software, Adhikary et al. [7,14] established three-dimensional numerical model for simulating the dynamic behaviors of RC beam members subjected to varying loading rates. The solid element and the beam element were respectively adopted for concrete and reinforcement. The material models in the software were used with the further incorporation of strain rate effect. Through the numerical modelling, the load versus mid-span deflection and the cracking patterns of RC beam members could be well captured (Figure 8). With the assumption of complete compatibility of strains between concrete and steel, the bond-slip was not considered in this study. Similar method for developing the dynamic numerical mode has been proposed by Zhao et al. [126]. Moreover, a simplified three-degree-of-freedom (TDOF) model was also proposed in [126] to investigate the dynamic shear behavior of RC beam members subjected to impact loading.

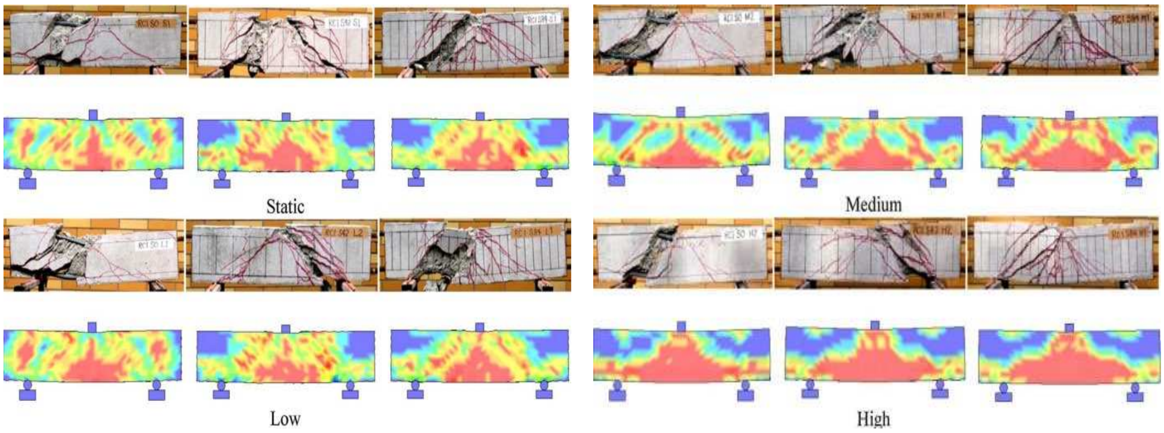
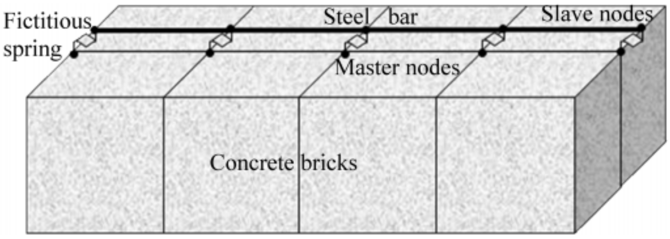
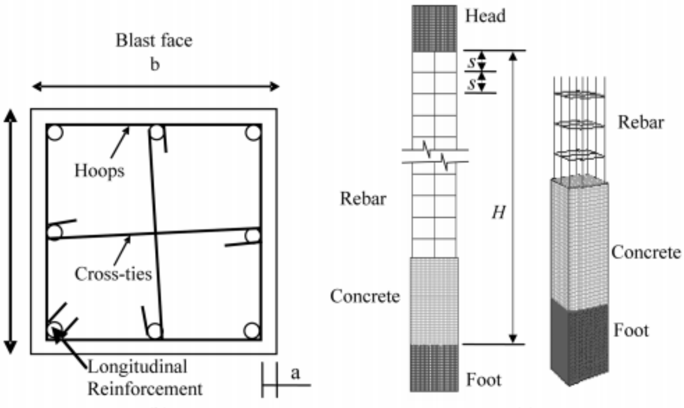


Figure 8. Comparisons between numerical and test results on cracking pattern for RC beam members under different loading rates [7].

It is noticed that for most of the numerical models considering the dynamic effect, perfect bond between the concrete and reinforcement materials was generally assumed. A few studies have been conducted on the establishment of dynamic numerical models for RC structural members. Based on the OpenSees software, the serial element model was developed by the authors [58] using the fiber beam-column element with plastic hinges. The dynamic numerical model incorporated the shear and bond-slip springs. It can well reflect the bearing capacity and stiffness degradation of structural members under different loading rates. Based on the LS-DYNA software, a one-dimensional slide line contact model was proposed by Shi et al. [127] for modelling the blast-induced dynamic responses of a RC column members considering the bond-slip effect (Figure 9). Based on the available material models in the LS-DYNA software, Rouchette [128] further incorporated the strain rate effect and used two orthogonal springs to simulate the bond-slip between concrete and steel. It was found that the accuracy of the FE numerical model could be improved as compared with the no-bond-slip model.



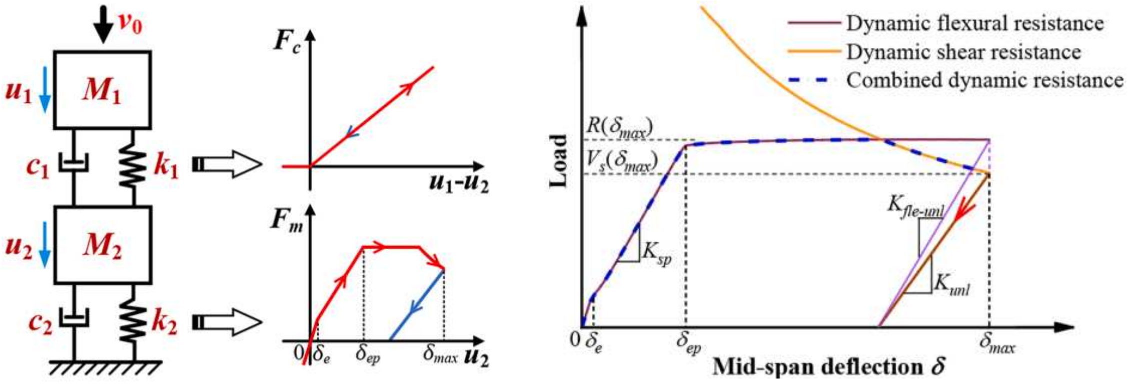
(**a**) Sketch of fictitious spring between master and slave nodes in one-dimensional slide line model



(**b**) Detached numerical model for RC columns

Figure 9. Schematic plot of numerical model for RC column members considering the dynamic effect and bond-slip between concrete and steel [127].

In addition to the above mentioned research works, several scholars have focused on the modelling the shear failure of RC structural members under dynamic loading rate. Valipour et al. [114] used the fiber element to establish numerical model for investigating the dynamic responses of RC beams and columns. The DIF models were adopted for considering the dynamic effect at the fiber level, and the shear cap was introduced at the section level to consider the possible failure of shear. Guner and Vecchio [129] developed a simplified method for the dynamic analyses of shear-critical RC frame members under impact and seismic load. In this study, the influences of dynamic effect and the shear effect were incorporated based on the DIF models and the rotating smeared crack approach, respectively. Lately, by introducing the combined dynamic flexural and shear resistance function, an improved two-degree-of-freedom (2DOF) model (Figure 10) was proposed by Jia et al. [130] to predict the possible failure modes (i.e. the punching shear, shear, flexure, flexure-shear and instability) of RC structural members subjected to low-velocity impact load.



(**a**) 2DOF numerical model

(**b**) Combined dynamic flexural and shear resistance function

Figure 10. Schematic plot of 2DOF model for RC structural members considering the dynamic effect and different failure modes [130].

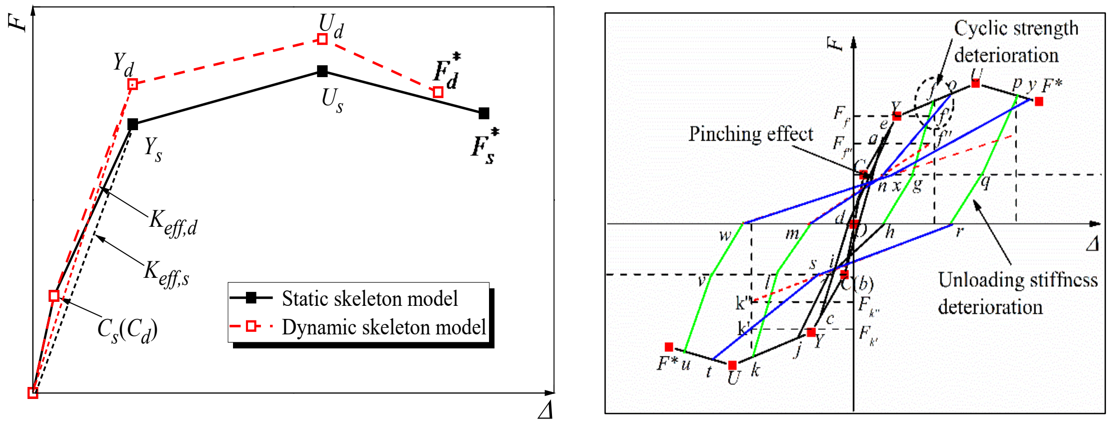
4.2.2. Hysteretic model considering dynamic effect

The hysteretic model is obtained by describing the load-deformation curve with skeleton and loading and unloading rules. Classical models include Clough [131], Takeda model [132], Ozcebe model [133], Park model [134], Bouc-Wen model [135], etc. With the continuous in-depth research on the restoring force characteristics of structural members, it has been realized that the degradation of bearing capacity and stiffness caused by material damage under cyclic dynamic load significantly affects the structural seismic performance [111]. Many hysteretic models considering different degradation effect factors, including strength degradation, stiffness degradation, pinching effect, negative stiffness segment, have been proposed, and the summary is shown in Table 4.

Table 4. Available hysteretic model considering different degradation effect factors.

Degradation effect factors		Relevant studies
Single factor	● Stiffness degradation	Clough [131], Takeda [132], Wen [135], Riddell[136], Takayanagi and Schnobrich [137], Zhu and Zhang [138], Saatcioglu et al. [139], Xu [140], Qu and Ye[141],
	● Pinching effect	Ambrisi and Filippou [142]
Multiple factor	● Stiffness degradation ● Strength degradation	Gu et al. [143], Zheng et al. [144], Zheng et al.[145], Erberik [146], Wang et al. [147]
	● Stiffness degradation ● Strength degradation ● Pinching effect	Roufeial and Meyer [148], Park and Ang [134], Ozcebe and Saatcioglu [133], Dowell et al. [149], Miramontes et al. [150], Pincheira et al. [151], Mostaghel and Byrd [152], Kunnath et al. [153], Yan et al. [154], Wang et al. [155], Yu et,al. [156], Sezen and Chowdhury [157], Leborgne and Ghannoum [158], Chao and Loh [159], Guo and Yang [160], Yu et al. [161], Cai et al. [162], Zhao and Dun [163], Huang et al. [164]
	● Stiffness degradation ● Strength degradation ● Negative stiffen ● Pinching effect	Song and Pincheira [165], Ibarra et al. [166], Guo and Long [167], Li [111]

In addition to the above models of macroscopic force-displacement, hysteretic models of RC structural members reflecting different deformation mechanisms have been proposed by researchers [168,169].It should be mentioned that the available hysteretic models were basically developed without the consideration of dynamic effect. Under dynamic loading, it is well known that the hysteretic behaviors of RC structural members are very different from those under static loading. To reasonably consider the influence of dynamic effect, an effective approach is to establish dynamic hysteretic model based on the available dynamic loading test data. Li et al. [113] developed the damage index-based dynamic hysteretic model for RC column members (Figure 11), taking into account the dynamic effect as well as the different degradation modes (i.e. strength degradation, stiffness degradation, pinching effect and negative stiffness segment). Combining with the usage of concentrated plastic hinge element, the numerical model can be applied to the structural dynamic analysis considering the real-time dynamic effect and seismic degradation of members.



(a) (b)

Figure 11. Illustration of hysteretic model for RC structural members considering the dynamic effect and different degradation modes [113].

4.3. Discussion on numerical simulation works

According of numerical simulation results on RC structural members under dynamic loading [58,115,117,119,170,171], it can be concluded that with the increase of loading rate, the bearing capacity and stiffness of structural members are enhanced whereas the deformation ductility is likely to be decreased. These numerical findings are in good agreement with the available dynamic loading test observations. It has also been shown in a few studies the cracking pattern, damage and failure mode can be well through numerical analysis [58,117,129,130]. Moreover, parametric studies have been carried out to investigate the influences of structural parameters on the dynamic behaviors of RC structural members [15,58,116,171].

As for numerical analysis at the level of overall structural, it has been demonstrated by available studies that the measured dynamic responses of RC structures in the experiments could be more accurately predicted with the inclusion of dynamic effect [119,172]. More importantly, the dynamic effect could exert a significant influence on the seismic responses, collapse assessment and fragility analysis of RC structures [118,173–176].

In terms of numerical simulation, there are still some shortcomings: (1) most of the FE numerical models fail to effectively consider the shear and bond-slip behaviors between concrete and reinforcement of RC structural members. Due to the lack of relevant models for RC members under dynamic loading, there is a need to develop numerical model of RC structural members effectively considering the dynamic effect on the shear and bond-slip behaviors; (2) the development of hysteretic model is largely dependent on the limited dynamic loading test data and the mathematical simplification, thus it is necessary to improve the model applicability and the computational efficiency; (3) by employing the refined numerical models and method considering the dynamic effect, further works need to be further carried on the seismic damage evolution and failure mechanism of RC structural members and structures.

5. Concluding remarks

Currently, most seismic design and dynamic analysis on RC structures are based on the large numbers of quasi-static experimental results but without the consideration of dynamic effect. Due to the insufficient test data under dynamic loading, there is still a lack of consensus on whether the dynamic effect of RC members needs to be considered in the structural design and analysis. In this paper, the research progress on dynamic behaviors of RC structural members are comprehensively reviewed from the experimental, theoretical and numerical perspectives. The results from available studies indicate that the influence of dynamic effect should be seriously taken into account if accurate and reliable seismic performance assessment of RC structures is desired. Despite the available research works, the future study is suggested in the following aspects:

(1) For dynamic loading tests, research works on RC structural members subjected to multidimensional dynamic load are needed to be further carried out. Moreover, more tests should be focused on the influence of dynamic effect on the deformation and damage mechanism of structural members. Furthermore, in-depth studies are required to investigate the influence law of dynamic effect on structural members with different parameters and failure modes.

(2) For dynamic modified models, the DIF models for RC materials are the mostly common used for considering the dynamic effect of RC structural members. Due to the randomness in structural members and external dynamic load, the reliability of dynamic modification at the material level to reflect the dynamic effect at the member level still needs to be further verified. In addition, the suitability and accuracy of the models proposed at the member level need to be improved based on supplementary data test data and advanced theoretical method.

(3) For numerical simulation analysis, there is a need to refine the available FE numerical models of RC structural members by incorporating the shear and bond-slip behaviors with the consideration of dynamic effect. Moreover, more efforts should be paid on the improvement of model applicability and computational efficiency. Furthermore, the seismic damage evolution and failure mechanism of RC structural members and structures need to be deeply investigated by utilizing the refined model and method for numerical simulation.

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