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Review

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

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Abstract: In this paper, research on dynamic behaviors of RC structural members was reviewed using experimental, theoretical and numerical perspectives. First, in a basic overview, measurement methods, main conclusions and current limitations of available dynamic loading tests were presented. Then, theoretical studies on the dynamic constitutive models of RC materials, the dynamic increase factor (DIF) model for concrete and reinforced steel and proposed modified models of dynamic behavior parameters at the structural member level were summarized. Finally, the available modeling approach and method for incorporating dynamic effects in numerical simulations of RC structures were reviewed. Moreover, the work involved a brief introduction to a dynamic hysteretic model established using experimental data, which was designed to provide an alternative approach to the commonly-used DIF method for considering these dynamic effects. This paper, therefore, aimed to provide a valuable reference for experimental studies and numerical simulations on the dynamic behaviors of RC structures—while also putting forward issues that need to be addressed by future work.

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

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1. Introduction

Reinforced concrete (RC) is one of the most widely-used building construction materials in civil engineering. In addition to static loads, RC structures may be subjected to different types of dynamic loads during their service life, such as explosion, impact, earthquake and wind load, etc. In past decades, a large number of RC structures have been damaged or even collapsed due to seismic hazards. Damage phenomena relating to different RC structures, e.g., public, residential and industrial buildings and bridges subjected to earthquake loads, are shown in Figure 1. According to statistical data, more than 10,000 people are impacted by earthquakes annually. This impacts are accompanied by economic losses totaling billions of U.S. dollars [1]. In order to reduce these human and economic losses, civil engineers and researchers have made great efforts to continually enhance the seismic performances of RC structures and to accurately evaluate their mechanical behaviors under earthquake load during the structural design, operation and maintenance stages.

It has been widely accepted that reinforcement and concrete exhibit different mechanical properties under static and dynamic loads, namely the strain rate sensitivity of the materials [2]. Consistent research findings concluded that, as the loading rate increased, the tensile strength and compressive strength of concrete—as well as the yield strength and ultimate strength of reinforcement were magnified. The elastic modulus and the strain, corresponding to the compressive strength of concrete, were also affected by the loading rate [3]. As for structural members consisting of RC materials, such as columns [4–7], beams [8–15], shear walls [16–19] and joints [20–24], changes in mechanical behaviors and failure patterns were observed for specimens under various loading rates, namely the dynamic effect at the member level. Different damage phenomena of RC structural members have been observed in response to seismic hazards, as shown in Figure 2. To acquire a better understanding of the dynamic behaviors of RC structural members under earthquake excitation, their performance must be comprehensively investigated, along with considerations of the seismically-induced loading rate. In the past half century, a number of dynamic loading tests have been carried out to deepen researchers' understanding of the mechanical behaviors of RC structural members that have been subjected to dynamic (i.e., blast, impact and seismic) loading rates. In addition, many researchers have performed numerical studies on the dynamic behaviors of RC structural members, specifically considering dynamic effects [25–28]. The advantages of numerical simulations, in relation to experimental tests, lie in the comparatively lesser manpower and material resources required for their execution. Additionally, they can more feasibly be applied to a wider range of structural parameters and loading rates. However, current seismic codes and most structural seismic analyses do not specifically consider the strain rate sensitivity of RC materials. The application of the dynamic increase factor (DIF) to modify the mechanical properties of RC materials, suggested by the CEB-FIP Model Code [29] and some other scholars [30–32], provided a common approach to consideration of the dynamic effects. Nevertheless, it should be noted that researchers have yet to achieve a deep understanding of the mechanisms by which the macro-mechanical behaviors of RC structural members under dynamic loads might be explained. To close the gap in this research area, several attempts have been made by scholars to establish dynamic modified models to consider dynamic effects at the member level, based on either experimental or numerical results [4,33,34].

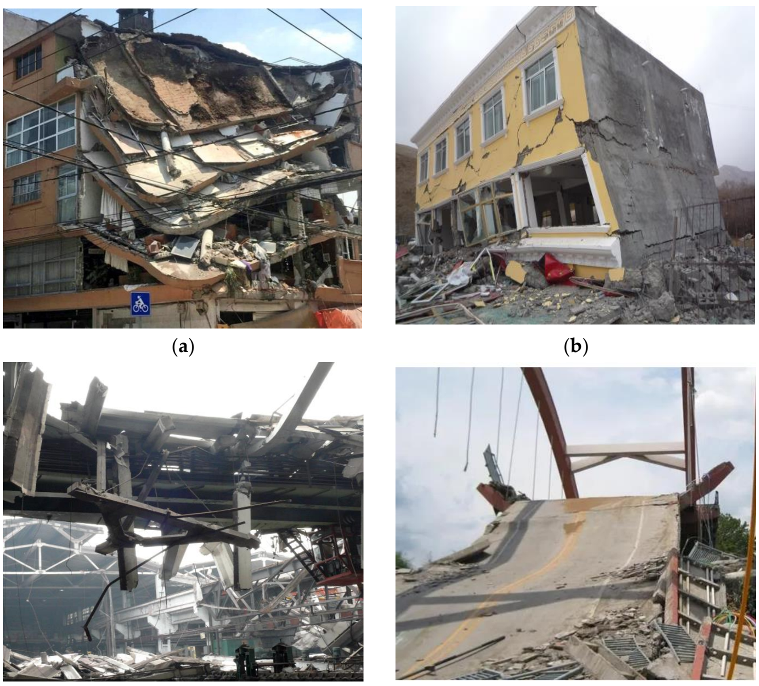

(a) (b) (c) (d)

Figure 1. Damage phenomena of RC structures under real earthquake load. (**a**) Damage to residential building; (**b**) Damage to public building; (**c**) Damage to industrial building; (**d**) Damage to bridge.

(a) (b) (c) (d)

Figure 2. Damage patterns in RC structural members after seismic hazards. (**a**) Damage to joint elements; (**b**) Damage to column elements; (**c**) Damage to wall elements; (**d**) Damage to beam elements.

In this paper, the existing research works were systematically summarized from experimental, theoretical and numerical perspectives. Additionally, prospective directions for future efforts were also outlined. This review paper aimed to provide a significant reference for seismic design and analysis works, thereby improving the seismic performances of RC structures.

2. Experimental Studies on Dynamic Behaviors of RC Structural Members

2.1. Overview of Dynamic Loading Tests on Structural Members

In the civil engineering field, several methods for testing the 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 [3]. Among these test methods, the pseudo-static test method is the most commonly used. By employing monotonic or cyclic loading schemes, the dynamic behaviors of RC structural members in the elastic stage, the plastic stage and the final failure stage can be obtained. However, one shortcoming of this method is that it cannot reasonably reflect the influences of strain rates or loading rates on the mechanical behaviors of RC structural members. Of the dynamic test methods, the shaking table test method provides the most accurate and reliable results; as such, it is often used to evaluate the dynamic responses and failure mechanisms of structural members and systems under earthquake excitations. However, it requires significant time and financial resources. In the earthquake observation test, seismic instruments need to be installed onsite, i.e., on a building, in order to measure the building's structural dynamic response under real earthquake conditions. In contrast, the pseudo-dynamic test method is often used to obtain information on the seismic actions of structures using the controlling approach through computational analysis [35].

At present, most available tests on RC structural members are carried out using static loading rates. In recent years, with advances in experimental techniques and improvements in our base 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. The most significant difference between the dynamic loading tests (10^{-4}/s < $\dot{\varepsilon}$ < 10^{1}/s) and the pseudo-static loading tests (10^{-6}/s < $\dot{\varepsilon}$ < 10^{-5}/s) was the magnitude of strain, or loading rate, exerted on the specimens.

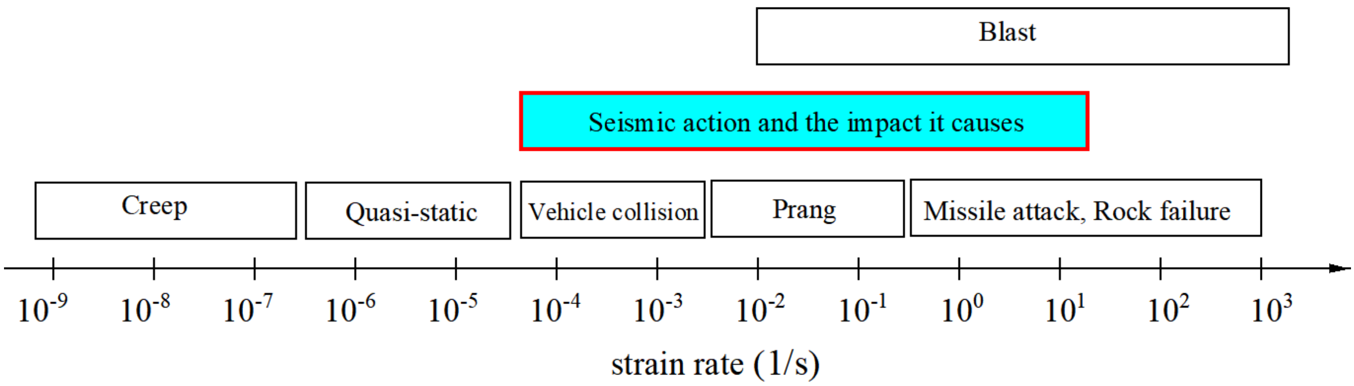


Figure 3. Strain rate range for RC structure under different dynamic loadings [36].

As an earthquake is a kind of dynamic load, dynamic loading tests provide results that more closely match the real-world seismic behaviors of RC structural members. Recent research on dynamic behaviors of RC structural members under impact and blast loading rates has been comprehensively reviewed [37–40]. However, research reviews of RC structural members upon subjection to seismic loading rates are, by comparison, lacking. Therefore, this paper mainly focused on dynamic loading tests of RC structural members carried out under earthquake-induced loading rates. Basic information on available dynamic loading tests (i.e., member type, specimen number, loading rate and scheme) is summarized in Table 1.

Table 1. Summary of dynamic loading tests performed on RC structural members subjected to earthquake loading rates.

No.	Reference	Type	Number	Loading Rate	Loading Scheme
1	Bertero et al. [41]	Beam	6	0.1, 10/s	Mono, cycl
2	Kulkarni and Shah [42]	Beam	14	0.0071–380 mm/s	Mono
3	White et al. [43]	Beam	4	0.0167–36 mm/s	Mono, Cycl
4	Zhang et al. [44]	Beam	36	1.05×10^{-5}, 1.25×10^{-3}/s	Mono
5	Marder et al. [13]	Beam	17	100 Hz	Mono, Cycl
6	Yan [45]	Beam	/	1×10^{-5}–1×10^{-3}/s	Cycl
7	Xiao et al. [46]	Beam	5	0.1–10 mm/s	Mono
8	Li and Li [11]	Beam	16	0.05–30 mm/s	Mono, Cycl
9	Zhou et al. [47]	Beam	7	0.06 mm–66 mm/s	Mono
10	Otani et al. [48]	Beam	8	0.1, 100 mm/s	Cycl
11	Guo [49]	Beam	12	0, 2, 6 m/s	Mono
12	Wu et al. [50]	Beam	3	87.89–135.8 Hz	Mono
13	Song et al. [5]	Beam	5	3.5–6 m/s	Mono
14	Adhikary et al. [8,10,15]	Beam	24	4×10^{-4}–2 m/s	Mono
15	Adhikary et al. [51]	Beam	30	0–5.6 m/s	Mono
16	Zeng [52]	Beam	6	10^{-2}/s–8.85 m/s	Mono
17	Feng et al. [53]	Beam	10	3–7.7 m/s	Mono
18	Mutsuyoushi and Machida [54]	Beam	14	0.1, 10, 100 cm/s	Mono, Cycl
19	Fukuda et al. [55]	Beam	48	4×10^{-4}–2 m/s	Mono
20	Yuan and Yi [56]	Beam	18	3.5×10^{-4}–1 m/s	Mono
21	Ye et al. [57]	Beam	14	0.8 m/s	Mono
22	Fujikake [14]	Beam	6	5×10^{-4} m/s, 2 m/s	Mono

Table 1. *Cont.*

No.	Reference	Type	Number	Loading Rate	Loading Scheme
23	Xiang et al. [58]	Column	7	/	Mono
24	Gutierrez et al. [59]	Column	3	0.02–1 Hz	Cycl
25	Bousias et al. [60]	Column	12	/	Cycl, Biax
26	Li et al. [61]	Column	30	0.000011–0.0167/s	Mono
27	Witarto et al. [6]	Column	4	0.05–5 Hz	Cycl
28	Perry et al. [62]	Column	4	0.7×10^{-4}–0.7×10^{-3}/s	Mono, Cycl
29	Yan [45]	Column	/	10^{-5}–10^{-2}/s	Mono
30	Zou et al. [63]	Column	/	10^{-5}–10^{-2}/s	Mono
31	Wang et al. [64]	Column	30	0.1–50 mm/s	Mono, Cycl, Biax
32	Jiang [65]	Column	12	0.1–20 mm/s	Mono, Cycl, Biax
33	Ghannoum et al. [35]	Column	10	0.25–1061 mm/s	Cycl
34	Liu et al. [66]	Column	10	0, 4.85, 6.86 m/s	Mono
35	Liu et al. [67]	Column	13	/	Mono
36	Lee et al. [68]	Column	6	/	Cycl
37	Wei et al. [69]	Column	6	4.95–5.42 m/s	Mono
38	Fan et al. [70]	Column	8	6.86, 5.42 m/s	Mono
39	Orozco and Ashford [71]	Column	3	0.22–1 m/s	Cycl
40	Shah et al. [72]	Joint	3	2.5×10^{-3}–1.0 Hz	Cycl
41	Chung and Shah [20]	Joint	12	0.0025–2.0 Hz	Cycl
42	Gibson et al. [73]	Joint	4	0–405 mm/s	Cycl
43	Pan [23]	Joint	10	0.1–10 mm/s	Cycl
44	Fan et al. [74]	Joint	3	0.4–40 mm/s	Cycl
45	Wang et al. [75]	Joint	8	0.4–40 mm/s	Cycl
46	Zhang [17]	Shear wall	7	10^{-5}–10^{-3}/s	Cycl
47	Xu et al. [16]	Shear wall	2	1–10 mm/s	Cycl
48	Chiu et al. [76]	Infill wall	6	0–0.4 g	Cycl
49	Yilmaz et al. [77]	Slab	9	4.43, 4.95, 5.42 m/s	Mono

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 schemes, respectively; 'Biax' denotes the specimen is loaded in two horizontal directions, as opposed to the default situation in the table, i.e., the specimen is loaded in a single horizontal direction.

From the summarized results, it was noted that there were fewer dynamic loading tests, as compared with static loading tests, and that the investigations primarily focused on beam and column members [5,8,35,54,59,72]. The majority of tests were conducted using electro-hydraulic servo loading systems. A few were carried out using drop-hammer impact testing machines. As earthquake loads are multidimensional in nature, it is reasonable to experimentally study the seismic performances of RC members and structures in space [9]. Wang et al. [78] studied the multidimensional dynamic behaviors of RC columns using two horizontal, and one vertical, electro-hydraulic servo actuators. Due to the difficulty of multi-axis loading testing and the higher requirements for testing equipment, the available literature and experimental data of multi-axis dynamic loading tests were inadequate [60,65].

2.2. Measurement Methods for Dynamic Loading Test

In dynamic loading tests, the observed quantities upon which researchers have focused include bearing capacity, displacement, strain, failure mode and cracks that can be directly measured or observed, as well as stiffness, ductility, damage and energy dissipation capacities—which need to be acquired indirectly. In the following sections, measurements of the test data were summarized in detail. Figure 4 shows the primary measured quantities of RC structural members in the dynamic loading tests.

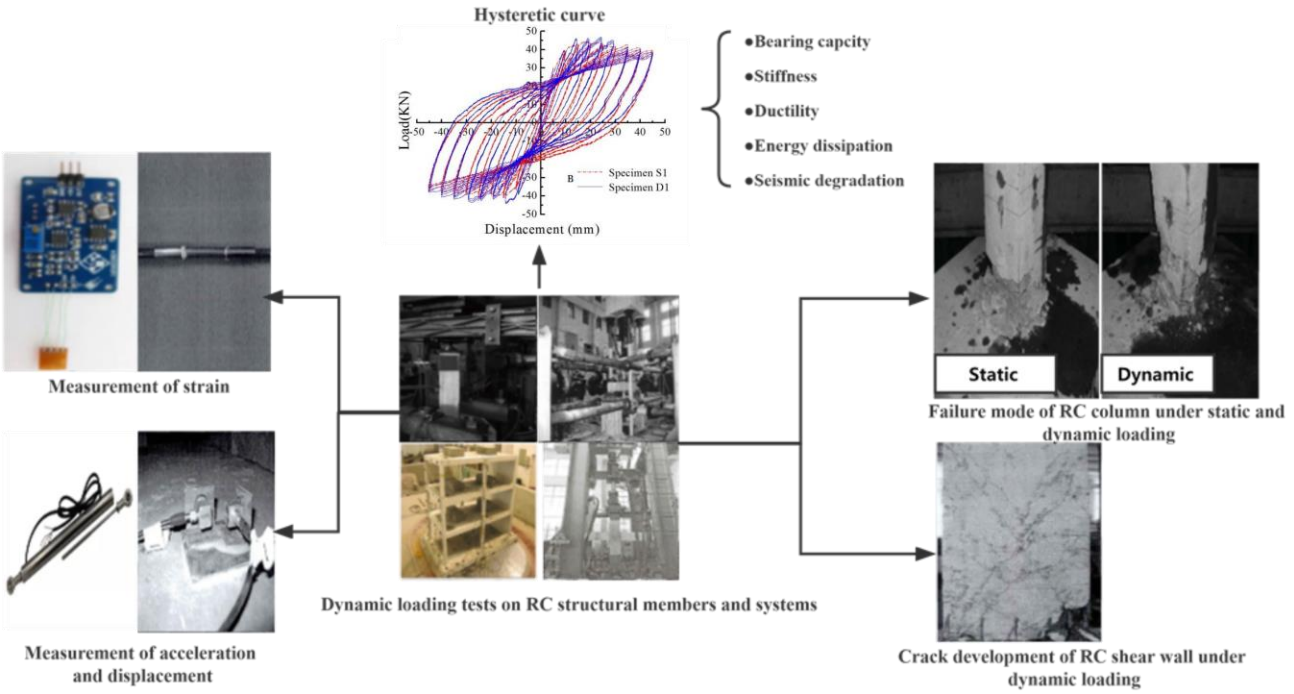


Figure 4. Measured quantities of RC structural members in dynamic loading tests.

To measure the force–displacement relationships between RC structural members, mechanical sensors, inside or outside of the loading device, have commonly been used to collect test data. For example, Wang et al. [78] used the force sensor and displacement sensor of a servo hydraulic actuator to measure the horizontal top displacement and bottom reaction force of the column specimens. Gutierrez et al. [59] used a mechanical sensor, installed in series with the piston rod of a servo device, to measure force, and used an LVDT sensor to determine displacement. In the dynamic loading test performed by Shunsuke et al. [48], a laser displacement sensor was used to measure lateral displacement and a strain gauge was used to measure deformation at a plastic hinge region.

In order to measure material strain on RC members, strain gauges are generally pasted either on the surfaces of structural members or on reinforcement inside them (Kenneth et al. [7], Wang [64], Long [79], Adhikary et al. [8]). Zhang [80] used a fiber Bragg grating strain sensor to measure concrete strain and further derive the real-time strain rate during the whole loading process. An acceleration sensor was employed to measure the horizontal and vertical acceleration of floors. Perry et al. [62] installed LVDT sensors between the two frames of a servo hydraulic testing machine to measure the longitudinal strain of columns members.

A few novel methods have been used by researchers to measure the displacement of RC structural members. For example, Liu [81] used planar trusses of LVDT sensors, arranged outside of the column specimen, to measure displacement. By using geometrical transformation, the flexural, shear and bond-slip deformation components of column specimens were indirectly determined. However, to the best of the authors' knowledge, few works have been reported on the changes in deformation components of RC structural members under dynamic loading rates. Zhang [17] arranged force and displacement meters at the four corners, as well as the bottom, of shear wall specimens in order to measure the displacement and shear deformation of the specimens under dynamic loading rates.

In general, failure modes and crack patterns in RC structural members can be directly observed with naked eyes [6,41,64,71]. However, in some dynamic loading tests, in which crack development was not feasibly or easily measurable, high performance measuring equipment has been employed as alternatives. For example, Adhikary et al. [51] used digital photography and high-speed cameras to capture the crack development and fracture process of RC beams during a drop hammer impact test. A similar approach was adopted by Ye et al. [57] who investigated the failure pattern and crack development of RC column members during impact loading.

Aside from the above physical qualities, which can be measured directly, damage and energy dissipation capacities 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 during the process of cyclic loading. The degradation of bearing capacity and stiffness, as well as the seismic damage and energy dissipation capacity, can be further derived by analyzing the test data of hysteretic loops [4,20,48,72]. By using a self-developed carbon nanofiber aggregate (CNFA) as an internal sensor—which was able to accurately capture the transient changes of structural force and stiffness with almost no time delay—Witarto et al. [6] detected seismic damage in RC column specimens under various loading rates.

2.3. Summary of Experimental Findings

As both concrete and reinforcing steel are rate-sensitive materials, their tensile and compressive mechanical properties are closely relevant to the loading rate. Consequently, the mechanical behaviors of RC structural members under different loading rates differ, which has been demonstrated by many experiments. Bertero et al. [41] experimentally studied the mechanical behaviors of RC simply-supported beams under high loading rates. They found that, with increased loading rates, the yielding bearing capacities of the members increased, whereas the ultimate bearing capacity did not change significantly. Additionally, the strain rate had a minor influence on the energy dissipation capacity, while members at higher loading rates were more likely to enter into brittle shear failure mode. Mutsuyoushi and Machida [54] found that, with increased loading rates, the failure of RC members tended to change, from flexural failure to shear failure. Kulkarni and Shah [42] carried out dynamic tests on RC simply-supported beams at different loading rates. As the loading rates increased, the failure modes of some specimens changed from shear to bending failure, contrary to the conclusions obtained by most researchers. Shah et al. [72] conducted cyclic loading tests of beam-column joints under different strain rates. It was observed that, with increased loading rates, the number of cracks lessened, while the damage intensified and the plastic deformation increased.

Available dynamic loading tests have shown that the 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. They determined that bearing capacity increased, while cracks and ductility decreased for specimens at higher loading rates. Additionally, the strain rate effect was more significant for specimens with lower reinforcement ratios. Li et al. [61] studied the mechanical behaviors of RC column members with different longitudinal reinforcement ratios, transverse stirrups and cross section shapes under uniaxial dynamic loading. It was observed that, with increased loading rates, the dynamic effects grew less obvious for specimens with higher strength concrete, while the influence of the cross-sectional shape was minor. Zhang et al. [44] conducted an experimental study on the fracture behavior of RC beams under different strain rates, considering the effects of the size of the specimens. The experimental results showed that the strain rate sensitivity values of specimens increased with increased specimen size. Fukuda et al. [55] 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 the loading rates on the ultimate bearing capacity of specimens was more significant for shear failure specimens than for flexural failure specimens. Adhikary et al. [8,10,15] carried out tests on a large number of RC beams at different loading rates, concluding that the dynamic effects grew more pronounced along with decreasing longitudinal reinforcement ratios or increasing shear span ratios. A large number of dynamic tests were carried out on reinforced concrete beams and columns by various authors [4,11,78,82,83]. They concluded that increased material strength and stirrup ratios would lead to decreased dynamic effects. Moreover, the strain rate sensitivity of the monotonic loading member was more significant than that of the cyclic loading member, and the areas of concrete crushing and falling off, as well as reinforcement buckling, were more localized.

2.4. Discussion on Dynamic Loading Tests

According to the available dynamic loading tests, the following consistent conclusions can be obtained: (1) with increases of the loading rate, the bearing capacity, stiffness and energy dissipation capacity of members are enhanced, while ductility may be reduced and the degradation of stiffness and bearing capacity may be aggravated. However, existing research works suffered from the following shortcomings: (1) in most of the dynamic loading tests, specimens were tested under nonaxial loading conditions. In order to more accurately reveal the dynamic behaviors of RC structural members, further experimental studies would be required, under multidimensional loading conditions; (2) Currently, the primary physical quantities measured in dynamic loading tests are stress, strain, displacement and force. There has not been sufficient experimental study of the influence of dynamic effects on the deformation and failure mechanisms of structural members; (3) As dynamic loading tests are inadequate, compared to traditional static loading tests, in-depth research will be needed to elucidate the influence of dynamic effects 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 influence of loading rates on the mechanical properties of concrete [84–98] and reinforcing steel [30,99–103] has been investigated by a large number of experimental studies. The rate sensitivity of concrete materials are influenced by many factors, including: (1) internal causes, such as dispersion in material properties, humidity [104–107] and the temperature [108,109]; (2) exterior causes, such as test loading method [110,111], equipment instability and measurement error, etc. After collecting test data on concrete under a wide range of loading rates (Figure 5), Pajak [110] found that the ratio of dynamic compressive strength to the corresponding static strength reached 3.5, whereas the dynamic tensile strength to the corresponding static strength reached 13. Moreover, it was pointed out by Bischoff [112] that the ratio of strain of the dynamic compressive strength to the corresponding static strain was in the range of 70~140%.

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 [113–119]. To reflect the influences of loading rates on the mechanical properties of concrete (e.g., the enhancement of compressive and tensile strength [2], the more brittle behavior for the descending branch of stress–strain curve [110]), the dynamic increase factor (DIF), which has been defined as the ratio of the mechanical behavior parameters of concrete under dynamic loading to the corresponding values under static loading, has become the most widely used. Notably, a few researchers removed the lateral inertia force and the end friction force of concrete specimens when obtaining DIF models [120,121]. Table 2 summarizes the commonly used models of dynamic increase factor (DIF) for concrete.

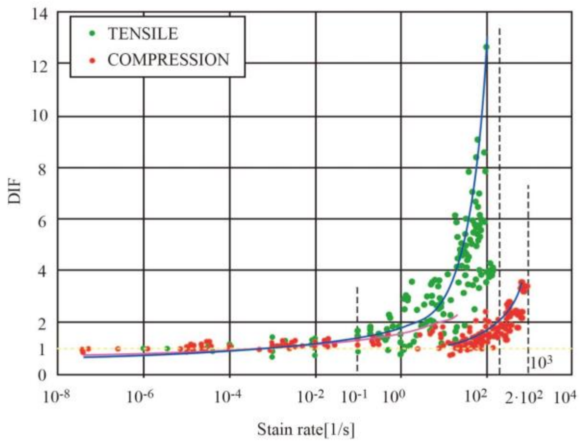


Figure 5. Statistical diagram of dynamic increase factor (DIF) for concrete tensile and compressive strength with variation in strain rate [110].

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

Model	Range of Dynamic Strain Rate	Quasi-Static Strain Rate	Type of Formula	Modified Parameters
CEB model [29]	$3.0 \times 10^{-5}/s \sim 300/s$	$3.0 \times 10^{-5}/s$ (compression) $3.0 \times 10^{-6}/s$ (tension)	Exponential	$f_{cd} E_{cd}\ \varepsilon_{cfd}\ f_{td}\ E_{td}$
Malvar model [122]	$10^{-6}/s \sim 160/s$	$1.0 \times 10^{-6}/s$	Exponential	f_{td}
Tedesco and Ross model [123]	$10^{-7}/s \sim 10^{2}/s$	$10^{-7}/s$	Linear logarithmic	$f_{cd} f_{td}$
Yan model [89]	$10^{-5}/s \sim 10^{-2}/s$	$10^{-5}/s$	Linear logarithmic	$f_{cd} E_{cd}\ f_{td}\ E_{td}$.
Xiao and Zhang model [124]	$10^{-5}/s \sim 10^{-1}/s$	$10^{-5}/s$	Linear logarithmic	$f_{cd} \varepsilon_{cfd}$
Li model [31]	$10^{-5}/s \sim 10^{-2}/s$	$10^{-5}/s$	Linear logarithmic	f_{cd}

Note: The values of quasi-static strain rate $\dot{\varepsilon}_0$ for compressive and tensile parameters are the same if not 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} denotes the dynamic strain, corresponding to the ultimate compressive strength of concrete.

To reflect the enhancement of yielding and ultimate strength under dynamic loading rates, researchers have established various dynamic constitutive models for reinforcing steel. For example, Johnson and Cook [125] developed the dynamic constitutive model of reinforcement, considering the combined influences of strain rate c effect and temperature. Morquio et al. [126] developed the predicted model for mechanical properties of reinforcement, considering strain rate sensitivity and size. Based on the thermo-visco-plastic theory, a dynamic constitutive model of reinforcement, applicable for a wide range of loading rates, was proposed by Rodríguez–Martínez [127]. Compared with the above models, the DIF models based on dynamic loading experimental results have been more widely employed. Table 3 summarizes commonly-used models of dynamic increase factor (DIF) for reinforcing steel.

As shown in Tables 2 and 3, the DIF models considered a variety of material strength degradation properties and a wide range of loading rates. Mechanical behavior parameters for dynamic modification include 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 can be obtained. They can then be used to establish dynamic constitutive models. More importantly, dynamic modified models at the material level can be utilized to determine the influences of dynamic effects on RC structural members.

Table 3. Commonly-used models 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 [29]	5.0×10^{-5} /s ∼ 10/s	5.0×10^{-5}/s	Linear logarithmic	f_{yd}, $f_{ud} f_{nd}$
Malvar model [122]	10^{-4} /s ∼ 10/s	3.0×10^{-4}/s	Exponential	$f_{yd} f_{ud}$
Lin Feng model [30]	< 2/s	3.0×10^{-4}/s	Linear logarithmic	$f_{yd} f_{ud}$
Li and Li model [103]	2.5×10^{-4} /s ∼ 0.1/s	2.5×10^{-4}/s 10^{-5}/s	Linear logarithmic	$f_{yd} f_{ud} \varepsilon_{hd}$

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.

3.2. Dynamic Modified Model at Member Level

Consensus was reached, among scholars, regarding the influence of loading rates on the mechanical behaviors of RC structural members. However, few works have focused on the mechanisms of the dynamic effects exhibited in experimental tests. These 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 [110]. (2) Inertial effects of member (Figure 6)—based on kinetic theory, the structural inertial force is magnified with the increasing loading rate and the constraints on the interior material are also intensified, resulting in the enhancement of macro bearing capacity and stiffness of structural members [128]. (3) Evolution of micro-cracks: due to limitations on time and space at higher loading rates, the probability of transfers of internal force in structural members and occurrences of bond-slip between concrete and reinforcement through stronger regions is increased [110].

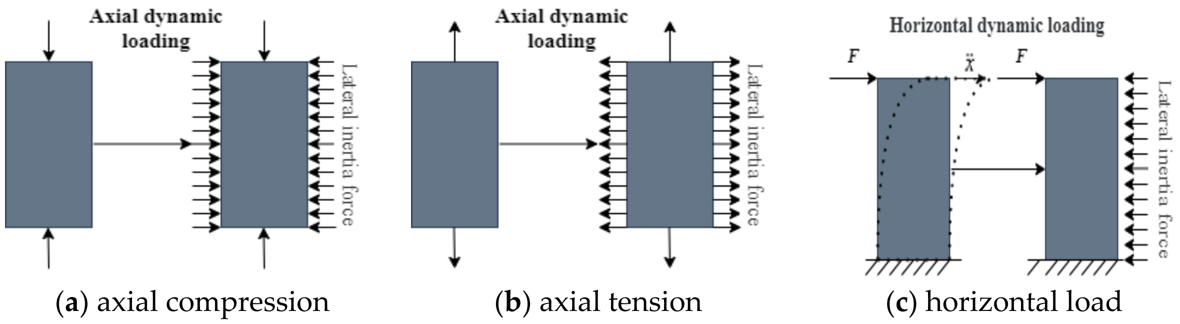


Figure 6. Schematic diagram of inertial effect for RC structural members under dynamic loading.

Due to the non-negligible dynamic effects on the mechanical behaviors of RC structural members, RC structural members exhibit different mechanical properties under static and dynamic loading (i.e., maximum bearing capacity, stiffness, ductility factor and hysteretic behavior). As scholars have done more comparative experiments on bearing capacities under various loading rates, the work counted dynamic increase factor (DIF) for bearing capacities of RC structural members with variations in strain rates, as shown in Figure 7. Data were taken from [5,8,10,11,14,15,17,19,23,45,47,49,51,52,55,56,64,65,67,74,129].

From the summarized results, it can be observed that, with increased loading rates, the dynamic increase factors (DIF) for the bearing capacities of RC structural members were enhanced. Additionally, as the orders of magnitude for strain rate increased, the increases for DIF for bearing capacities grew more and more significantly. However, different scholars studied different types of RC structural members (i.e., beams, columns and shear walls) with different design parameters. As such, there were certain disparities in the summary results. In addition, as bearing capacity impacts the macro-mechanical behavior of RC structural members, it was difficult to determine the influences of dynamic effects on the mechanical behaviors of RC structural members at the member level.

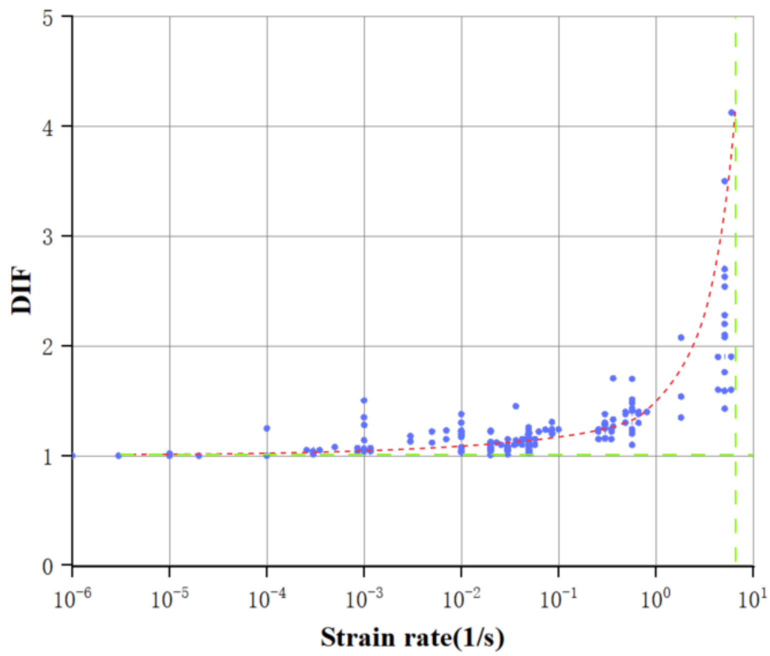


Figure 7. Statistical diagram of dynamic increase factor (DIF) for bearing capacity of RC structural members with variations in strain rates.

Scholars have made attempts to establish dynamic modified models to aid in considering dynamic effects at the member level. Zhan et al. [130] developed the dynamic modified model to predict the maximum and residual deflection of RC beam members based on a significant quantity of experimental data. Adhikary et al. [8] developed a dynamic modified model to evaluate the ultimate bearing capacity for RC beam members based on a large quantity of numerical simulation results utilizing the LS-DYNA software. They also studied the influences of longitudinal reinforcement ratios and transverse stirrup ratios on the dynamic modified factors of RC beam members. By using the dynamic modified material constitutive model, Wang et al. [64] established a finite element model of RC column members using the OpenSees software. Accordingly, the expressions of DIF (i.e., the ratios of dynamic mechanical behavior parameters to the corresponding static parameters at the member level) for ultimate bearing capacity of columns, considering axial load ratios, concrete strength and longitudinal reinforcement ratios, were obtained. Fan et al. [22] derived the calculation equations for shear strength of concrete and developed a modified model for predicting the dynamic shear bearing capacity of RC joints through multiple linear regression analyses of test data, considering the influences of dynamic effects and axial forces. Based on the dynamic loading test database of RC column members and the Bayesian update theory, Li et al. [33] proposed a probabilistic model of DMC (dynamic modified coefficient) to evaluate the yielding and ultimate bearing capacity, effective stiffness and displacement ductility ratios for RC column members under dynamic loading. The proposed modified models were able to accurately and reliably predict the mechanical behaviors of column members under seismic loading rates. Table 4 lists some of the representative dynamic modified models for RC structural members developed using finite element (FE) simulation or experimental results.

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

Reference	Equations of Dynamic Modified Model	Model Type
Adhikary et al. [8]	Maximum resistance of RC regular beams (1) With transverse reinforcements $DIF = \left[1.89 - 0.067\rho_g - 0.42\rho_v - 0.14(a/d)\right]e^{[-0.35-0.052\rho_g+0.179\rho_v+0.18(a/d)]\delta}$ (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. [15]	Maximum resistance of RC deep beams (1) With transverse reinforcements $DIF = \left[1.25 - 0.04\rho_g - 0.13\rho_v + 0.05(\frac{a}{d})\right]e^{[0.22-0.03\rho_g-0.17\rho_v+0.03(a/d)]\delta}$ (2) without transverse reinforcements $DIF = \left[0.45 + 0.09 + 0.48(\frac{a}{d})\right]e^{[0.30-0.05\rho_g-0.05(a/d)]\delta}$	FE simulation results-based (Deterministic)
Wang [64]	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 $DIF = 1.0 + c_f \lg\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s} \quad c_f = 1 \times 10^{-4} f_c^2 - 0.068 f_c + 0.153$ (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. [33]	Mechanical behavior parameters of RC columns (including yielding and ultimate bearing capacity, effective stiffness and ductility coefficient) $DMC_j(\mathbf{x}, \boldsymbol{\Theta}) = \sum_{i=1}^{6} \theta_i h_i(\mathbf{x}) + \sigma\varepsilon = \theta_1 f_y / f_c' + \theta_2 n_0 + \theta_3 \lambda + \theta_4 \rho_l + \theta_5 \rho_s + \theta_6 \lg(\dot{\varepsilon}_d / \dot{\varepsilon}_0) + \sigma\varepsilon$	Experimental date-based (Probabilistic)
Fan [74]	Shear bearing capacity of RC joints $DIF = 0.99679 + 0.1536n + 0.02326\lg\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$	Experimental date-based (Deterministic)
Yan [45]	Elasticity modulus of RC beams (1) With transverse reinforcements $\frac{E_d}{E_s} = 1.3247(\dot{\varepsilon})^{0.027}$ (2) Without transverse reinforcements $\frac{E_d}{E_s} = 1.2486(\dot{\varepsilon})^{0.0213}$	Experimental date-based (Deterministic)
Song [5]	Dynamic increase factor in flexural strength of RC column $DIF_m \approx DIF_s \times \frac{1 - \frac{1}{2}\frac{\sigma_y}{f_c}\frac{DIF_s}{DIF_c}\rho_s + \frac{1}{2}\frac{\sigma_y'}{f_c}\rho_s' - \eta}{1 - \frac{1}{2}\frac{\sigma_y}{f_c}\rho_s + \frac{1}{2}\frac{\sigma_y'}{f_c}\rho_s' - \eta}$	FE simulation results-based (Deterministic)
Rouchette et al. [34]	Simplified formula for mid-span deflection of RC beams under impact loading $Di = Ds \times (1 + \frac{1.77E+18}{c^2} V^2)$	FE simulation results-based (Deterministic)

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

3.3. Discussion on Dynamic Modified Models

To accurately evaluate the dynamic behaviors of RC structural members, quite a large number of research works have focused on the establishment of dynamic constitutive models and DIF models of concrete and reinforcing steel materials, as well as the development of dynamic modified models at the member level. Strictly speaking, many of these studies were carried out using methods that were partially theoretical and partially empirical. As such, they cannot be separated from experimental tests. Drawbacks of the available research works included: (1) The most commonly used method to determine dynamic effects on RC structural members is to modify static constitutive model parameters using DIF models at the material level. However, whether dynamic modification at material levels can effectively reflect dynamic effects on the mechanical behaviors of structural members has not been adequately verified. (2) The usage of dynamic modified models proposed at the member level provides a direct and efficient approach, reflecting the influences of dynamic effects on the mechanical behaviors of RC structural members. Due to inadequate test data, the suitability and accuracy of the models need to be improved. (3) The mechanisms underlying the dynamic effects on the mechanical behaviors of structural members remains an unsolved problem; it must be thoroughly investigated.

4. Numerical Studies on Dynamic Behaviors of RC Structural Members

4.1. Overview of Numerical Studies Considering Dynamic Effect

To date, the dynamic behaviors of RC structural members and structures have been numerically investigated, considering dynamic effects, by many researchers. The merits of numerical simulations, with respect to experimental tests, are primarily that they require fewer human and material resources, that they are repeatable, and that they can be applied to a broader range of structural parameters and loading rates. The computational accuracy and reliability of numerical results are directly dependent on the methods used to simulate structural dynamic behaviors.

Two currently-available methods through which to consider dynamic effects in numerical simulation of RC structures, i.e., the dynamic constitutive model (DCM) method and the dynamic increase factor (DIF) method [28]. The DCM method requires tedious and time-consuming computation; thus, it is used less frequently in engineering practice and research. The DIF method has been more frequently adopted by researchers. Quite a few studies have used this method to investigate the influences of dynamic effects on the seismic behaviors of RC members and structures [131–139]. The disadvantages of the DIF method include [28]: (1) it cannot fully reflect the adverse impacts of dynamic effects on the structural displacement ductility and performance degradation; (2) the influence of dynamic effects on the shear and bond-slip behaviors of RC structural members has generally been neglected.

Moreover, due to randomness in structural members (e.g., geometric sizes, material properties and reinforcement conditions) and external dynamic loads, a few attempts have been made to consider dynamic effects in a probabilistic manner [140]. Simplified or alternative methods for considering strain rates in materials have been proposed by researchers [25,141,142]. Through numerical simulations, the effectiveness and reliability of the proposed numerical models and methods have been validated with test data, and the influences of dynamic effects 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

To aid in developing reasonable FE models for RC structural members, different materials, element types and modeling techniques have been adopted by researchers, based on available FE software or self-compiled programs. Table 5 summarizes basic information on FE models (i.e., member type, element type, parameter and numerical effectiveness) of RC structural members subjected to dynamic loading rates.

Table 5. Summary of FE models on RC structural members subjected to varying loading rates.

Reference	Type	Elements	Parameter	Effectiveness
Wang [64]	Column	Solid element and truss element	Strain rates	Correlation between strain and strength under unidirectional dynamic loading test.
Wang [26]	Column	Three-dimensional fiber beam and birth–death element	Loading scheme Strain rate	User material subroutine for RC structural members considering the strain rate effect of materials.
Liu and Li [27]	Column	Three-dimensional fiber beam and birth–death element	Strain rates Damage	The dynamic behaviors of RC beams and column members.
Adhikary et al. [10]	Beam	Solid and beam element	Strain rates Inertia Longitudinal reinforcing ratio Stirrup ratio Shear span ratio Dynamic shear resistance	The dynamic shear resistance of RC deep beams was found to increase as the loading rates were increased.

Table 5. *Cont.*

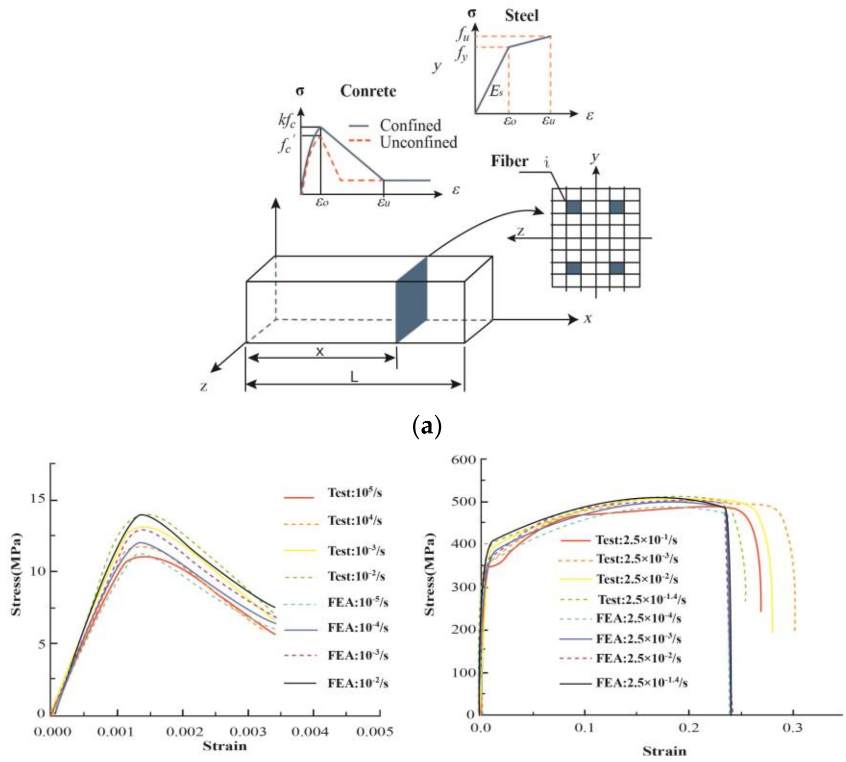
Reference	Type	Elements	Parameter	Effectiveness
Zhao et al. [139]	Beam	Solid and Hughes–Liu beam elements	Strain rates Beam span Shear Impact mass Reinforcement ratio Sectional dimension	The resistance characteristics of localized shear failure of RC beam members subjected to varying loading rates.
Wang [64]	Column	Fiber beam-column element with plastic hinges	Strain rates Shear Bond-slip Axial compression ratio Longitudinal reinforcement ratio Shear span ratio Concrete strength	Reflected the bearing capacity and stiffness degradation of structural members under different loading rates.
Shi et al. [143]	Column	One-dimensional slide line model	Strain rates Shear Slip Damage	The blast-induced dynamic responses of RC column members considering the bond shear modulus, maximum elastic slip strain and damage curve exponential coefficient.
Rouchette et al. [34]	Beam	3-D spar element, solid element, bond-link element	Strain rates Corroded steel bar Flexural Bond-slip Impact mass Beam geometry Concrete strength Reinforcement ratio The solicitation force	Simulated the flexural behavior of reinforced concrete beams considering the bond between concrete and steel bar under impact loading. The accuracy of the FE numerical model could be improved, as compared with the no-bond-slip model.
Valipour et al. [131]	Beam	Fiber element	Strain rates Shear Impact mass	Dynamic analysis of reinforced concrete beams subjected to high strain rate loads considering the possible failure of shear.
Guner and Vecchio [144]	Shear wall	Secant-stiffness-based finite-element algorithm	Strain rates Shear	A simplified method for the dynamic analyses of shear-critical RC frame members under impact and seismic load. The influences of dynamic effects and the shear effect were incorporated based on the DIF models and the rotating smeared crack approach.
Jia et al. [137]	Beam	2DOF model	Strain rates Flexural Shear Impact mass Reinforcement ratio Concrete strength	Predicted 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.
Adhikary et al. [15]	Beam	Hughes–Liu beam element and solid element	Strain rates Shear Bond-slip Impact mass	The relationship between failure mode and impact mass of RC beam members under impact load.
Li et al. [145]	Beam	Hughes–Liu beam element with 2 × 2 Gauss quadrature	Strain rates Impact energy Inclination angle of drop weight Concrete strength	Investigated the dynamic behavior of beams subjected to impact loading rates. The influences of dynamic effects and excessive distortion due to large deformations under impact loads were incorporated, based on the DIF models and a method to automatically remove the distorted elements, based on predefined criteria.

Table 5. *Cont.*

Reference	Type	Elements	Parameter	Effectiveness
Yang [138]	Shear wall	Solid and truss element	Strain rates Shear span ratio Reinforcement ratio Failure mode	Mechanical property and failure mode subjected to dynamic loading rates.
Song and Zhang [18]	Shear wall	Solid and truss element	Strain rates Shear span ratio Axial compression ratio	The response of RC shear wall with different shear span ratios and axial compression ratios under quasi-static load and dynamic load with high strain rate.

A summary is shown in Table 5, above, demonstrating finite element models of RC structural members subjected to varying loading rates. Most scholars drew unanimous conclusions with their experiments. Similar to the experiment, beam and column members are mostly investigated. Otherwise, RC structural members exhibited different failure modes, cracking patterns, and damages upon being subjected to static and dynamic loading rates. Many scholars have paid attention to these behaviors. Studies, like those above, have also demonstrated the efficacy of numerical analyses.

Based on the ABAQUS software, the detached model of RC column members was established by one of the authors [64], using the solid element and the truss element, respectively, to simulate concrete and reinforcing steel. The dynamic effects were included through modification of static material parameters in the damage plastic model of concrete and the ideal elastoplastic model of reinforcement with the corresponding DIF models [29,30]. 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. [26] developed the user material subroutine for concrete and reinforcement, considering the strain rate effects of the materials. It was suitable for use with the three-dimensional fiber beam element on the ABAQUS software and could be further applied to nonlinear dynamic analyses and progressive collapse assessments of RC and steel structures. On the basis of this research work, the model was refined by Liu et al. [27], who incorporated the strength and stiffness deterioration levels induced by accumulated damage to the material. These have been shown to provide better simulation results for dynamic behaviors of RC beams and column members. The effectiveness of the subroutine and the proposed beam-column element (Figure 8a) were also verified by Zhang et al. [136], who numerically simulated the dynamic responses of a shaking table test frame structure. The DIFs of micro-concrete and iron wire, developed on the test data (Figure 8b), were used to represent the material dynamic properties in the beam-column models. Based on the ABAQUS software, the responses of RC shear walls with different shear span ratios and axial compression ratios, under quasi-static load and dynamic load with high strain rate, were studied. The failure modes and bearing capacities of shear walls under various shear span ratios, axial compression ratios and strain rates were also compared (Figure 9) by Zhang [17].



(**a**)

(**b**)

Figure 8. Schematic plot of dynamic fiber model for RC beam-column members employing the user material subroutine. (**a**) The proposed fiber beam-column element; (**b**) Stress–strain curves of micro-concrete and iron wire at different strain rates [136].

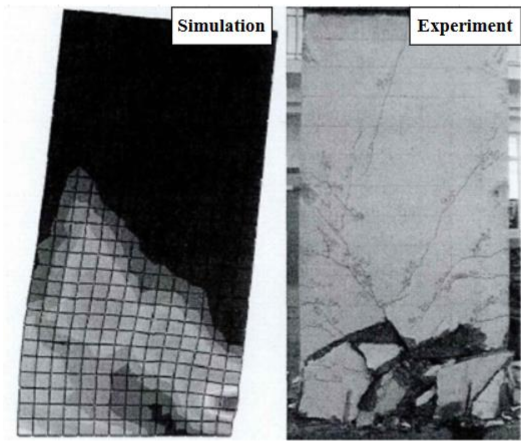


Figure 9. Damage to RC shear wall obtained from test and simulations [17].

Using LS-DYNA software, Adhikary et al. [8,15] established a 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 adopted, respectively, for concrete and reinforcement. The material models in the software were used with the further incorporation of strain rate effects. Through numerical modeling, the load versus mid-span deflection and the cracking patterns of RC beam members were captured (Figure 10). Due to the assumption of complete compatibility of strains between concrete and steel, the bond-slip was not considered in this study. A similar method for development of dynamic numerical modes was proposed by Zhao et al. [139]. Moreover, a simplified three-degree-of-freedom (TDOF) model was proposed to facilitate investigation of the dynamic shear behavior of RC beam members subjected to impact loading.

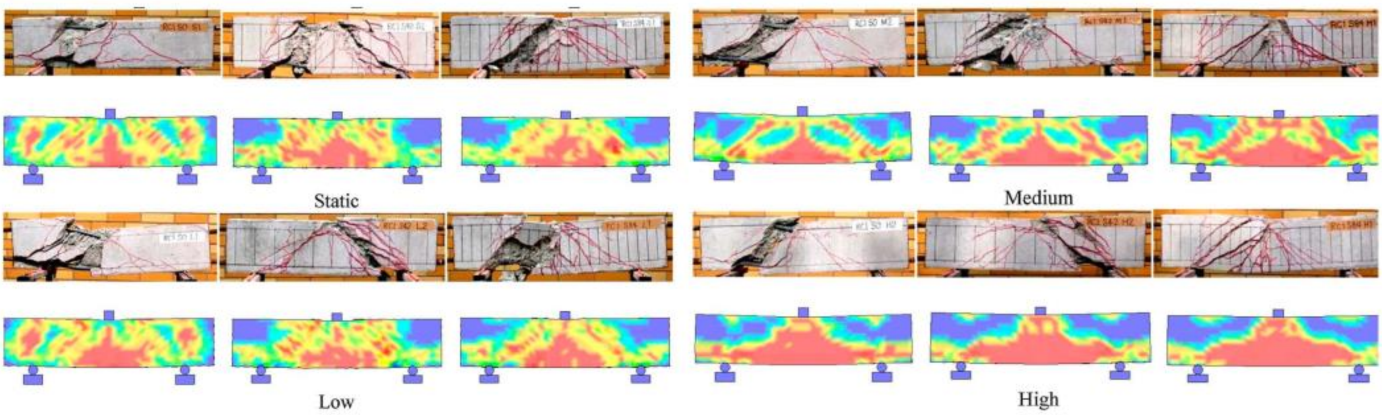


Figure 10. Comparisons between numerical and test results on cracking patterns for RC beam members under different loading rates [8].

It was noted that, for most of the numerical models considering dynamic effects, perfect bonds between the concrete and reinforcement materials were generally assumed. A few studies were conducted based on the establishment of dynamic numerical models for RC structural members. Using OpenSees software, a serial element model was developed by the authors of [64], using a fiber beam-column element with plastic hinges. The dynamic numerical model incorporated the shear and bond-slip springs. It was able to accurately reflect the bearing capacity and stiffness degradation values of structural members under different loading rates. Using LS-DYNA software, a one-dimensional slide line contact model was proposed by Shi et al. [143] that focused on modeling the blast-induced dynamic responses of RC column members, considering the bond-slip effect (Figure 11). A 3-D mesoscale numerical model was established by Jin et al. to investigate the impact resistances of RC beams under different combinations of mass and velocity [146]. The effects of the combination of impact mass and velocity on the failure modes of RC beams were simulated and compared with experimental results (Figure 12). Based on the available material models in the LS-DYNA software, Rouchette [34] 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, as compared with the no-bond-slip model, left room for improvement.

In addition to the above mentioned research works, several scholars focused on modeling the shear failure of RC structural members under dynamic loading rates. Valipour et al. [131] used a fiber element to establish a numerical model and investigate the dynamic responses of RC beams and columns. DIF models were adopted to consider dynamic effects at the fiber level, and the shear cap was introduced at the section level to consider possible shear failure (Figure 13). Guner and Vecchio [144] developed a simplified method for dynamic analyses of shear-critical RC frame members under impact and seismic loads. In this study, the influences of dynamic effects and the shear effect were incorporated based on the DIF models and the rotating smeared crack approach, respectively. Recently, after introducing the combined dynamic flexural and shear resistance function, an improved two-degree-of-freedom (2DOF) model (Figure 14) was proposed by Jia et al. [137] that aimed to predict possible failure modes (i.e., punching shear, shear, flexure, flexure-shear and instability) of RC structural members subjected to low-velocity impact loads.

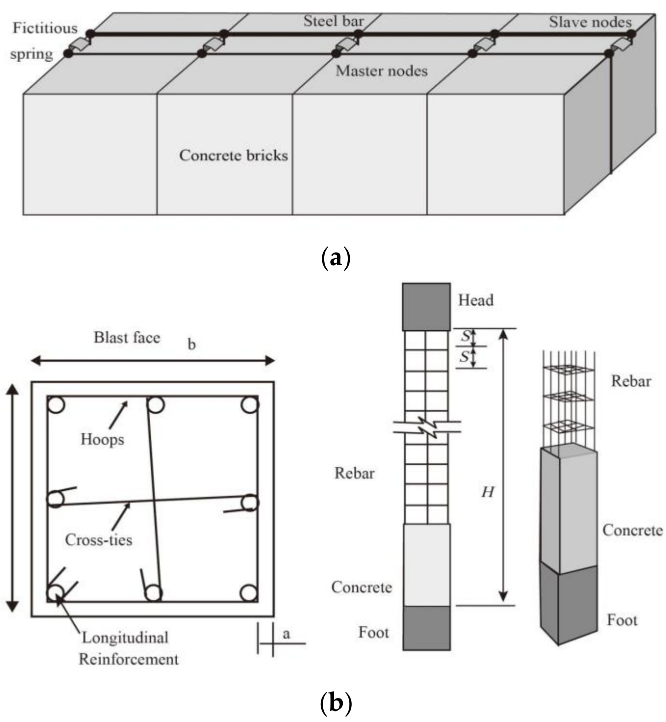


Figure 11. Schematic plot of numerical model for RC column members considering the dynamic effect and bond-slip between concrete and steel. (**a**) Sketch of fictitious spring between master and slave nodes in one-dimensional slide line model. (**b**) Detached numerical model for RC columns [143].

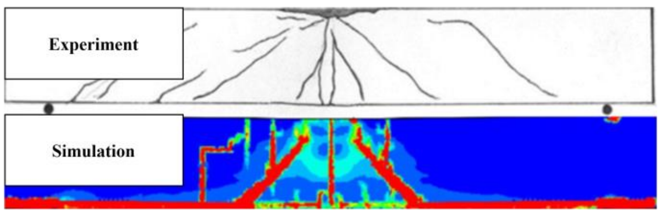


Figure 12. Failure patterns of RC beams obtained from tests and simulations [146].

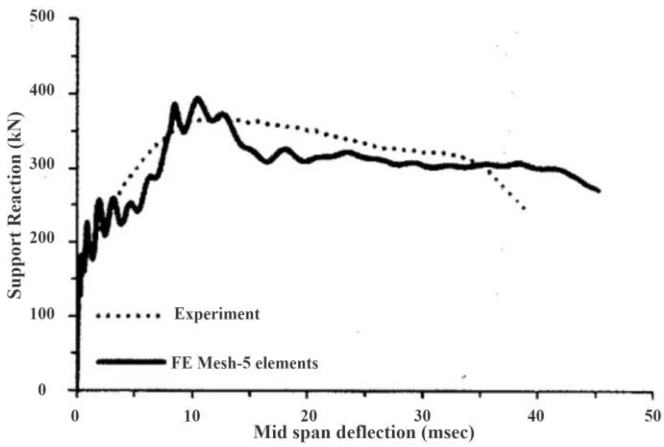
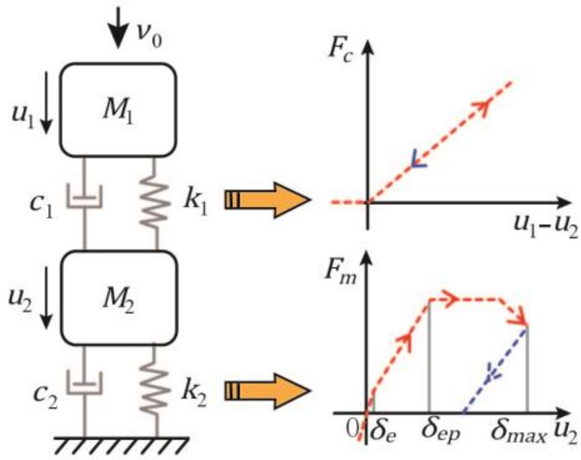
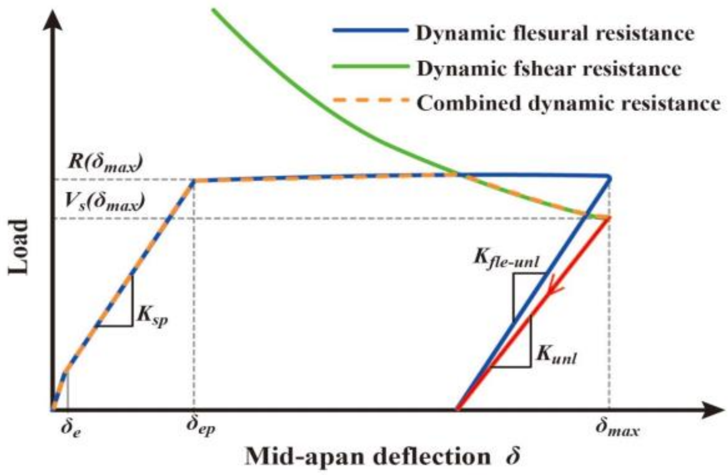


Figure 13. Comparison of experimental results and numerical simulations of mid-span deflection versus support reaction for RC beam [131].



(a)



(b)

Figure 14. Schematic plot of 2DOF model for RC structural members considering the dynamic effect and different failure modes. (**a**) 2DOF numerical model; (**b**) Combined dynamic flexural and shear resistance function [137].

4.2.2. Hysteretic Model Considering Dynamic Effect

The hysteretic model was obtained by describing the load-deformation curve with skeleton and loading and unloading rules. Classical models include Clough [147], Takeda model [148], Ozcebe model [149], Park model [150], Bouc-Wen model [151] and others. With the continuous in-depth research on restoring force characteristics of structural members, researchers have determined that the degradation of bearing capacities and stiffness caused by material damage under cyclic dynamic loads significantly affects the structural seismic performance [33]. Many hysteretic models have been proposed which considered different degradation effect factors, including strength degradation, stiffness degradation, pinching effect and negative stiffness segment. A summary is shown in Table 6.

Table 6. Available hysteretic model considering different degradation effect factors.

Degradation Effect Factors		Relevant Studies
Single factor	• Stiffness degradation	Clough [147], Takeda [148], Wen [151], Takayanagi and Schnobrich [152], Saatcioglu et al. [153], Xu [154], Qu and Ye [155],
	• Pinching effect	Ambrisi and Filippou [156]
Multiple factor	• Stiffness degradation • Strength degradation	Gu et al. [157], Zheng et al. [158], Zheng et al. [159], Erberik [160], Wang et al. [161]
	• Stiffness degradation • Strength degradation • Pinching effect	Park and Ang [150], Ozcebeand Saatcioglu [149], Dowell et al. [162], Mostaghel and Byrd [163], Yan et al. [164], Wang et al. [165], Yu et al. [166], Sezen and Chowdhury [167], Leborgne and Ghannoum [168], Chao and Loh [169], Guo and Yang [170], Yu et al. [171], Cai et al. [172], Zhao and Dun [173], Huang et al. [174]
	• Stiffness degradation • Strength degradation • Negative stiffen • Pinching effect	Song and Pincheira [175], Ibarra et al. [176], Guo and Long [177], Li [33]

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 [178,179]. It should be mentioned that the available hysteretic models were basically developed without consideration of dynamic effects. Under dynamic loading, hysteretic behaviors of RC structural members differ greatly from those under static loading. To consider the influences of dynamic effects, an effective approach might be to establish dynamic hysteretic models based on available dynamic loading test data. Li et al. [28] developed a damage index-based dynamic hysteretic model for RC column members (Figure 15), taking into account dynamic effects as well as different degradation modes (i.e., strength degradation, stiffness degradation, pinching effect and negative stiffness segment). Combined with the usage of concentrated plastic hinge elements, the numerical model could be applied to structural dynamic analyses considering the real-time dynamic effects and seismic degradation of members.

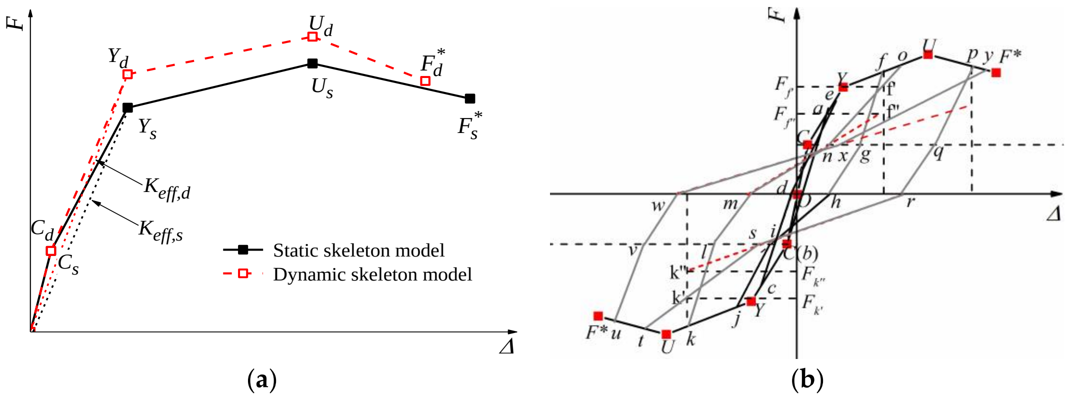


Figure 15. Illustration of hysteretic model for RC structural members considering dynamic effects and different degradation modes. (**a**) Static and dynamic skeleton models; (**b**) Hysteretic rules [28].

4.3. Discussion on Numerical Simulation Works

According to numerical simulation results involvingRC structural members under dynamic loading [64,129,132,134,136,180], it was concluded that, with increased loading rates, bearing capacities and stiffness values of structural members were enhanced, whereas deformation ductility were likely to be decreased. These numerical findings were in good agreement with available dynamic loading test observations. It has also been shown, in multiple studies, that cracking patterns, damage and failure modes can be accurately reflected through numerical analysis [64,134,137,144]. Moreover, parametric studies have been carried out to investigate the influences of structural parameters on the dynamic behaviors of RC structural members [16,64,129,133].

As for numerical analyses at overall structural levels, it was demonstrated by available studies that the measured dynamic responses of RC structures in experiments could be more accurately predicted if dynamic effects were included for consideration [136,181]. More importantly, dynamic effects could exert significant influence on seismic responses, collapse assessments and fragility analyses of RC structures [1,25,135,182–185].

In terms of numerical simulation, some shortcomings remain: (1) most of the FE numerical models have failed 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 rates, there is a need to develop numerical models of RC structural members that effectively considering dynamic effects on shear and bond-slip behaviors. (2) The development of hysteretic models is largely dependent on limited dynamic loading test data and mathematical simplification. Thus, it will be necessary to improve model applicability and computational efficiency. (3) Employing refined numerical models and methods that consider the dynamic effects, further works must be undertaken to reveal the seismic damage evolution and failure mechanisms of RC structural members and structures.

5. Concluding Remarks

As RC buildings have been widely constructed and used in civil engineering, enhancing their seismic performances and improving the accuracy of seismic evaluations would play a very important role in reducing the huge human and economic losses induced by earthquakes. The relatively large strain rates found in RC materials may be observed in structural members under seismic load and compared with those observed under static load. Meanwhile, the strain rate-sensitivity of materials could result in changes in the dynamic behaviors of RC structural members—changes that must not be neglected. However, most current seismic designs and dynamic analyses of RC structures have been based on a large number of quasi-static experimental results without considering dynamic effects. Moreover, there is still a lack of consensus regarding whether the dynamic effects of RC members need to be considered for more reliable structural design and analysis. To date, a large number of experimental and numerical studies have focused on the dynamic behaviors of RC structural members under impact and blast load. During the past few decades, many research works have focused on the dynamic behaviors of RC structural members subjected to seismic-induced loading rates. In this paper, research progress on this topic was comprehensively reviewed from experimental, theoretical and numerical perspectives. The main conclusions have been summarized as follows:

(1) According to the statistical results of available experiments on RC structural members under dynamic loading rates and seismic load, many tests have been performed on RC beams and column members under uniaxial loading schemes and static and dynamic loading rates. As compared with high loading rate tests, the experiments under median loading rates have been inadequate.

(2) In several experimental studies, structural parameters were designed to be different in order to facilitate investigation of their influences on the dynamic behaviors of RC structural members. Most dynamic loading tests measured bearing capacity, displacement, strain, crack development and failure patterns. In addition, seismic damage and energy dissipation were indirectly acquired in a number of experiments.

(3) Based on the results of available dynamic loading tests, the following conclusion was reached: with increased loading rates, the bearing capacity, stiffness and energy dissipation capacity of members were enhanced, while ductility might be reduced, and the degradation of stiffness and bearing capacity aggravated. As for failure mode, research findings have not led to consistency or consensus.

(4) To reflect the influences of loading rates on the mechanical properties of RC materials, the DIF models established on the dynamic loading tests have been the most widely

used. By summarizing the DIF models for concrete and reinforcing steel, it was determined that the mechanical behavior parameters for general dynamic modification included compressive strength, tensile strength, elastic modulus of concrete and the yielding strength and ultimate strength of reinforcing steel.

(5) The mechanism of dynamic effects on RC structural members under seismic load could be explained by the strain rate-sensitivity of materials, the inertial effects of members and evolutions of micro-cracks. However, few research works have focused on this issue. Dynamic modified models for mechanical behavior parameters of RC structural members have been developed using finite element (FE) simulation or experimental results. These models considered the influences of loading rates and different structural parameters, and could be directly applied to estimate the dynamic behaviors of RC structural members.

(6) Base on available FE software and self-compiled programs, various numerical methods have been undertaken by researchers to establish FE models to simulate the dynamic behaviors of RC structural members under different loading rates. Moreover, the dynamic hysteretic model established on the dynamic loading test data provided an effective approach to reasonably consider the influences of dynamic effects.

(7) Through comparison with the test data, it was noted that more accurate results could be obtained using numerical models and methods that considered dynamic effects. In a few studies, cracking patterns, damage and failure modes of RC structural members were accurately captured through numerical simulations. Moreover, numerical studies could be applied to a broader range of structural parameters and loading rates, facilitating parametric analyses of the dynamic behaviors of RC structural members.

Given the research gaps in the available literature, the following could be suggested directions for future research:

(1) For dynamic loading tests, more research on RC structural members subjected to multidimensional dynamic loads should be carried out. Moreover, more tests should focus on the influence of dynamic effects on the deformation and damage mechanisms of structural members. Furthermore, in-depth studies are required to elucidate the influence of dynamic effects on structural members with different parameters and failure modes.

(2) Among dynamic modified models, DIF models are the most commonly used to consider the impact of dynamic effects on RC structural members. Due to randomness in structural members and external dynamic loads, the capability of dynamic modification, at the material level, to reliably reflect dynamic effects at the member level should be 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 methodologies.

(3) For numerical simulation analysis, researchers should refine the available FE numerical models of RC structural members by incorporating shear and bond-slip behaviors with their consideration of dynamic effects. Moreover, more effort should be applied to improving model applicability and computational efficiency. Furthermore, the seismic damage evolution and failure mechanisms of RC structural members and structures must be deeply investigated, utilizing refined models and methods for numerical simulation.

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