Study on the Impact Mechanical Properties of RC Beams in Local Response Stage

Yifei Xu[1], Xiaocong Yuan[2], Ruicheng Qiu[1], Fei Zhao[1], Wanli Yang[3,4*]

[1]Sichuan Communication Surveying and Design Institute Co.,Ltd., Chengdu, 610017, China
[2]China Road and Bridge Engineering Co.,Ltd., Beijing, 100010, China
[3]School of Civil Engineering, Xinjiang Institute of Engineering, Urumqi, 830000, China
[4]School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031, China

*Corresponding author, Email: 68360903@qq.com

Abstract. The nonlinear dynamic response of RC beams under impact loads exhibits typically characteristics of two stages: local and global response. The duration of the local response stage is extremely short, and the beam itself is featured with obvious inertial and shear effects, which makes the impact damage mechanism of the RC beam exceptionally complex. Therefore, the ABAQUS explicit dynamic module is used in this paper to establish a three-dimensional finite element model of the RC simply supported beam impacted by the drop hammer, aiming to study the dynamic mechanical behavior of the RC beam in the local response stage in a comprehensive way, and the effectiveness of the modeling methods and techniques are verified by the available experimental results. Given this, the nonlinear mechanical behaviors of RC beams in different response stages are analyzed in detail in this paper, and the influence of impact velocity and shear bending ratio on the shear effect and ultimate failure modes of the specimen are investigated, as well.

Keywords: RC beam, Dynamic mechanical, Impact load, Failure mode, Shear effect

1 Introduction

Accidents such as ships hitting bridge piers, falling objects from vehicles hitting bridge superstructures, and falling rocks hitting buildings in mountainous areas may give rise to local damage or even monolithic collapse of engineering structures. Therefore, great importance should be attached to the impact load in the structural design [1]. As a common force component in structures, the nonlinear dynamic response of reinforced concrete (RC) beams under impact load is of great significance to the impact resistance design of structures. Nowadays, many studies around the world have been focused on the mechanical properties of RC beams under impact loads based on experiments and numerical simulations. Xu Bin et al. [2] investigated the impact resistance of RC beams under different impact masses, impact velocities, and impact energies, as well as secondary impacts by using a drop hammer impact test system. It was found that the beams

G. Zhao et al. (eds.), *Proceedings of the 2024 6th International Conference on Civil Architecture and Urban Engineering (ICCAUE 2024)*, Advances in Engineering Research 262,
https://doi.org/10.2991/978-94-6463-688-8_45

were prone to form obvious diagonal oblique cracks in the area near the impact point. Moreover, the shear failure of the specimen becomes more prominent with the increase of impact velocity. The research findings of Zhao et al. [3] is the same as that of above research, and they reckon that the sensitivity of different strain rates of steel bars and concrete is the main reason for the shear failure of RC beams. Tachibana et al. [4] conducted low-velocity impact experiments on RC beams with different span lengths, section dimensions and reinforcement ratios. The impact load characteristics and dynamic mechanical behavior of RC beams were evaluated by analyzing the impact force and mid-span displacement time courses, damage modes of specimens, as well as energy dissipation rules. Additionally, a formula for calculating the maximum deflection of RC beams based on the impact energy and static flexural load carrying capacity estimation was proposed. Kishi et al. [5, and Zhao et al. [6] further modified the formulas by considering the effects of damage mode and the mass ratio of the beam to the hammer on this basis. Saatci et al. [7] have studied the influence of hoop ratio on the impact resistance of RC beams, finding that the impact force is almost resisted by inertial force before the stress wave is transmitted to the supports. Pham et al. [8] have conducted impact simulations on RC beams under different boundary conditions, indicating that the boundary conditions have little impact on the impact force, but exerts a great influence on the damage and displacement of longer beams. To sum up, the current research on the nonlinear dynamic response of RC beams under impact load mainly focuses on the response characteristics of the beam in the overall response stage and its influencing factors, as well as impact design methods and damage assessment criteria. On the contrary, there are scarce studies on the dynamic mechanical behavior of RC beams in the local response stage. However, in the local response stage, RC beams are often subjected to complex forces and have significant shear effects. Only on the premise that the shear failure does not occur in the local response stage, the bending failure can be guaranteed in the overall response stage. At the same time, the damage degree of the local response stage will also affect the bearing capacity of the overall response stage [9]. Accordingly, Zhou et al. [10] studied the damage behavior of stainless steel reinforced concrete beams under impact load, and proposed empirical formula for calculating the internal force of the beam disturbance zone in the local response stage. Obviously, current studies have not fully analyzed the mechanical characteristics and shear damage mechanisms of RC beams in the local response stage.

To this end, a finite element model of the RC beam under the impact of drop hammer is established in this study in view of the experimental results of Zhou et al. [11]. To begin with, the dynamic response history of RC beam under impact load is analyzed in detail in this paper, so as to summarize the nonlinear response characteristics of the beam in the local response stage and the overall response stage. In the following, the shear effect and dynamic balance force system (that is, the effect of impact force and inertial force) in the local response stage are studied in depth. The research in this paper can provide theoretical support for the impact resistance design of engineering structures. Before the design of engineering structures, brittle shear failure should be prevented during the local response stage under impact load.

2 Numerical Simulation and Verification

2.1 Overview of the Experiment

In order to verify the accuracy of the finite element model, this study uses the ABAQUS explicit dynamics module to carry out the finite element simulation of the ultra-high drop-weight impact experiment of reinforced concrete beams conducted in reference [11]. The design parameters of the selected three specimens are shown in Table 1. Each beam had a designed total length of 2,000 mm, with its clear span of 1,800 mm and section dimension of $b \times h = 150\,\text{mm} \times 300\,\text{mm}$. The design strength of concrete was C40, and the thickness of the reinforcement cover was 25 mm. The average compressive strength of the standard cube test block was 45.3Mpa, and the elastic modulus was 3.25×104Mpa. Three beam bottom bars and auxiliary bars were symmetrically arranged with one row of two grade III ordinary steel bars (HRB400). The stirrups configuration was HPB300, an ordinary steel bar with its grade being I and its diameter of 8 mm, and the properties of the reinforcement material are presented in Table 2. The impact test device and its detailed parameters can be found in reference [11]. The mass of the drop hammer in the test was set to 400 kg, and the drop hammer was dropped along the vertical guide rail at 0.5 m from the top of the beam to the mid-span of the simply supported beam.

Table 1. Information on Specimen Design

Specimen no.	Bottom bars	Auxiliary bars	Stirrup	Reinforcement ratio	Shear bending ratio (V/P)	Shear span ratio
Beam-L18	2Φ18			1.04%	166.74/113.63	
Beam-L20	2Φ20	2Φ10	φ8@150	1.63%	166.74/136.41	0.45
Beam-L25	2Φ25			2.57%	166.74/192.43	

(Note: The design flexural strength P and shear strength V of the beam are calculated according to the study of Zhou et al. [11].)

Table 2. Properties of Reinforced Materials

Fiber type	Modulus of Elasticity (MPa)	Yield strength (MPa)	Ultimate strength (MPa)
HPB300	2.10×10^5	302	425
HRB400	2.00×10^5	420	620

2.2 Establishment of Numerical Model

The finite element model of the RC beam impacted by the drop weight is shown in Fig. 1. The entire drop hammer is simplified as a cylinder with a diameter of 200 mm in this paper, so as to ensure that the contact area of the beam and the hammer can completely conform to the experimental conditions. The impact velocity of the drop hammer is set to 2.25 m/s through the initial predefined field, and the material density of the drop hammer is adjusted in the material properties to make its mass reach 400 kg. The initial distance between the drop hammer and the upper surface of the RC beam has been set to 2 mm. The dimensions of the beam section, the restraint method at its both ends and the reinforcement forms are consistent with the experiment. The contact forms between the drop hammer and the beam, as well as the beam and the bottom support are all set as general contact. And the contact properties are defined as "Hard Contact" in the normal direction, with a friction coefficient of 0.15 in the tangential direction. In the whole impact simulation process, except for the use of three-dimensional truss elements (T3D2) for discrete reinforcement, the concrete, the supports and drop hammer are all set as 3D solid element (C3D8R). In addition, unit hourglass control is introduced in the process. The grid dimensions of concrete and steel bars are divided into 10 mm and 25 mm respectively by taking the mesh sensitivity into full account, aiming to improve the computational efficiency of the model and the reinforcement cage is directly embedded in the concrete matrix during the simulation.

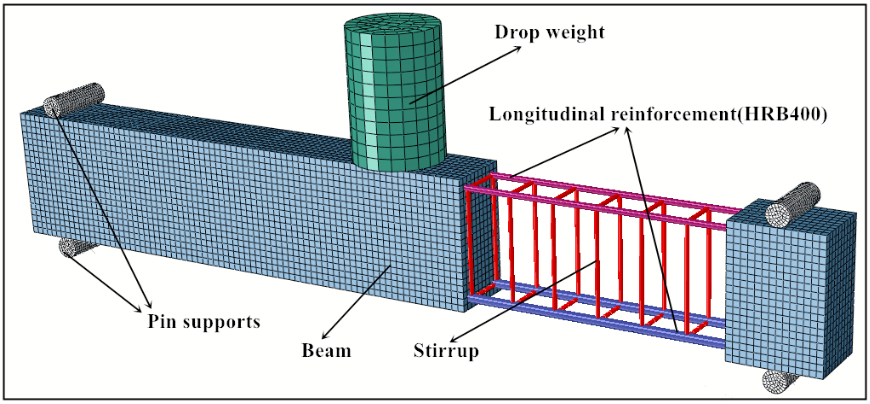


Fig. 1. Model of Drop Hammer Impacting RC Beam

As far as material properties are concerned, the elastic model is used to describe the mechanical behavior of the drop hammer and the base, both of them being set as rigid bodies. The base is determined according to the steel performance parameters, with its density being 7850 kg/m^3, the elastic modulus of 2.1 GPa, and the Poisson's ratio being 0.15. Despite the fact that the elastic modulus and Poisson's ratio of the drop hammer are the same as those of the base, its density depends on the mass of the drop hammer.

The concrete is simulated by Concrete Damaged Plasticity (CDP) provided in ABAQUS, and its main control parameters are shown in Table 3. This model has been well applied in simulating the nonlinear dynamic response of reinforced concrete structures [11]. When the concrete is in the elastic stage, the stress strain relationship curve of concrete can be described by Young's modulus and ultimate elastic stress. However, when the concrete is in the inelastic stage, its stress strain relationship curve is described with reference to the constitutive model recommended in the Chinese standard GB-2010 [11] in this paper, In this specification, the evolution parameters of concrete tensile and compressive damage are introduced into the formula, respectively.

The proposed calculation method in CEB code [11] is used to characterize the amplification of concrete dynamic tensile and compressive strength when considering the strain rate effect of concrete material under impact load. Moreover, the model proposed in reference [11] is expected to be used for calculation in terms of the amplification of the elastic modulus of concrete. The bilinear elastic plastic model is used to simulate the ordinary steel bar, with the material parameters consistent with the experiment and the Cowper-Symond model [11] is introduced in this paper to clarify the hardening of the strain rate of steel under impact load. Please note that the bond-slip effect between steel bars and concrete has not been considered in the model.

Table 3. Parameters of Concrete Materials

Concrete properties in ABAQUS	
Elastic modulus, E_0 (MPa)	32500
Poisson's ratio, ν	0.2
Mass density(kg/m^3)	2450
CDP concrete material parameters	
Dilation angle, ψ	32°
Eccentricity, e	0.1
f_{b0}/f_{c0}	1.162
K	0.6667
Viscosity parameter, μ	0.0005

2.3 Validation of Numerical Model Results

The comparison of the impact force and the time history curve of the mid-span displacement through the experiment and numerical simulation is shown in Fig 2.

It can be seen from the Fig. 2 that the experimental error of the peak impact force is small, all between 10% and 20%. However, there is a slight deviation in the oscillation section, which is mainly caused by the overshoot of the piezoelectric signal source during the experimental data acquisition process [9]. Therefore, the impact force time history measured by the experiment has a negative value in the shock stage, but on the whole, the development trend of the impact force time history obtained by the two is generally the same. At the same time, the time history curves of mid-span displacement obtained by simulation and experiment are basically consistent, with the experimental errors of displacement peak values all within 10%.

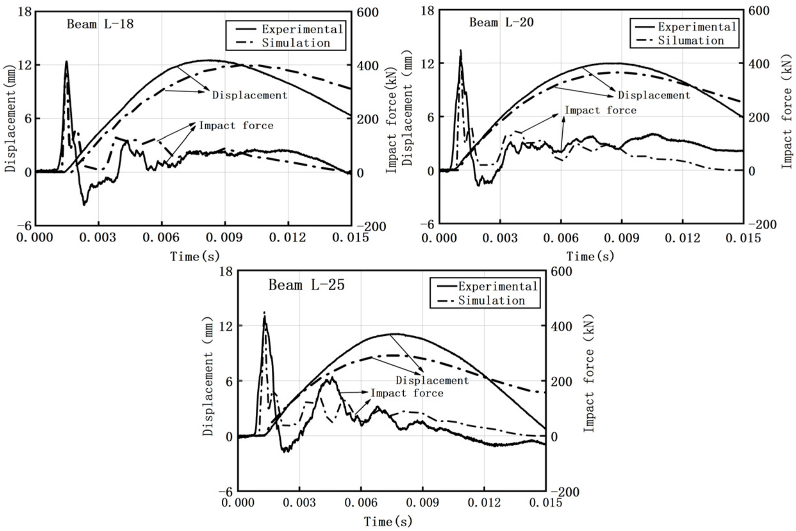
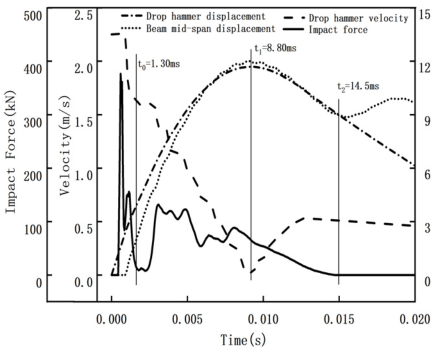


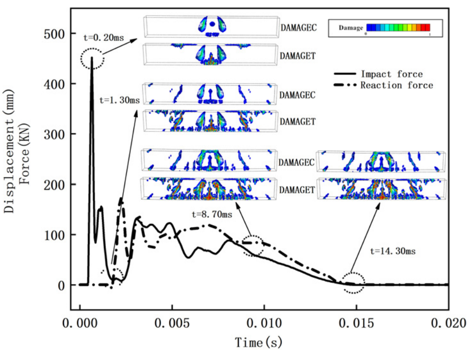
Fig. 2. Diagram on Time History Comparison between Impact Force and Mid-span Displacement

3 Nonlinear Dynamic Response of RC Beam

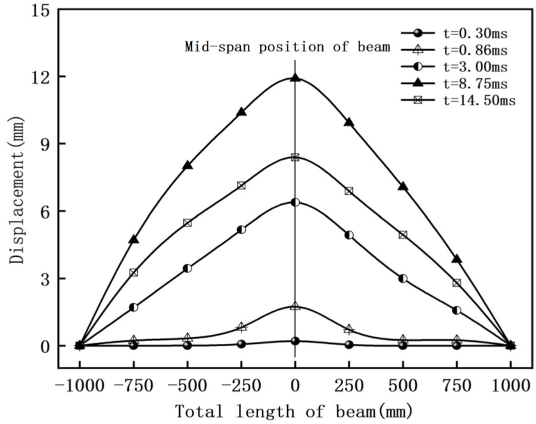
On the basis of the results of the drop hammer impact experiment and finite element simulation, the dynamic response characteristics of the RC beam at different stages are analyzed in detail in this section. The specimen Beam-L18 is taken as an example in this section. It can be seen that the dynamic response history of the entire beam to hammer collision system includes the following three stages when taking time into consideration.



(a)Impact Force, Displacement of Beam Mid-span, as well as Velocity and Displacement Time History of Drop Hammer



(b) Time History of Impact Force and Reaction Force



(c) Dynamic Deformation Time History of the Beam

Fig. 3. Time History of Dynamic Response

The first stage is the local response stage (0-1.30 ms): the duration of this stage is extremely short, with its impact force rising sharply and reaching its peak around 0.2 ms. Then, the impact force drops rapidly and approaches 0, forming a pulse trough. Therefore, it can be seen from the Fig. 3 (b) that the stress wave generated by the impact has not yet reached the supports at both ends of the beam in this stage. This means that the reaction force does not respond, and the impact force is generally resisted by the inertial force. During this period, the beam is only slightly deformed in the local area of the mid-span, with its maximum displacement less than 3 mm (Fig. 3(c)). There develop shear damage zones in the collision contact area and under the mid-span of the beams owing to peak impact and inertial forces. However, damage to the specimen does not develop in its way given the short duration of this stage. As a result, the overall damage of the specimen at the end of this stage is relatively light. The second stage is the overall response stage (1.30ms-8.80ms): after the point of 1.30ms, the stress wave is transmitted to the supports at both ends of the beam to form the reaction force. The beam begins to respond as a whole under the influence of the impact force, the reaction force of the support, as well as the inertial force, and releases the impact energy in the form of deformation and cracking. It can be concluded from the Fig. 3(a) and Fig. 3(b) that when the mid-span displacement of the beam reaches the peak value, the drop velocity will become zero, and all its kinetic energy is converted to the beam body. The damage of the beam as a whole reaches its peak at this moment, and the shear damage zone at an angle of 45° under the impact point is its main damage area. It can be concluded that the shear effect of the specimen in the local response stage has a huge impact on the failure modes and bearing capacities in the overall response stage. This also indicates that the shear effect of the RC beam under impact load is formed in the local response stage, and fully developed in the overall response stage. Furthermore, it can be found from Fig. 3(b) that the development trend of the reaction force and the impact force is generally the same after the point of 1.8ms. This shows that in the dynamic balance force system of the impact force, the reaction force and the inertial force, the inertial force mainly acts at the initial moment in the local response stage and the overall response stage, which proves that the influence of the impact force and inertial force in the local response is the root cause for the formation of shear effect. The third stage is the rebound stage (8.80ms-14.50ms): after the point of 8.80ms, the elastic deformation stored by the beam itself is capable of leading the beam and the drop hammer to rebounding upward together. Besides, the velocity of the drop hammer gradually accelerates, being out of contact with the beam at the point of 14.50ms. In this stage, the impact force gradually decreases and eventually reaches 0, with its mid-span displacement gradually dropping and forming residual displacement in the end.

4 Analysis of Shear Damage Mechanism

In this section, the shear effect and the final failure mode of the RC beam under different impact velocities and the shear bending ratio of the specimens are involved in order to analyze the influence of the shear effect in the local response stage. The information of the five specimens used in the model is shown in Table 4, and the plastic damage cloud diagram of each specimen corresponding to the impact load is presented in Fig. 4.

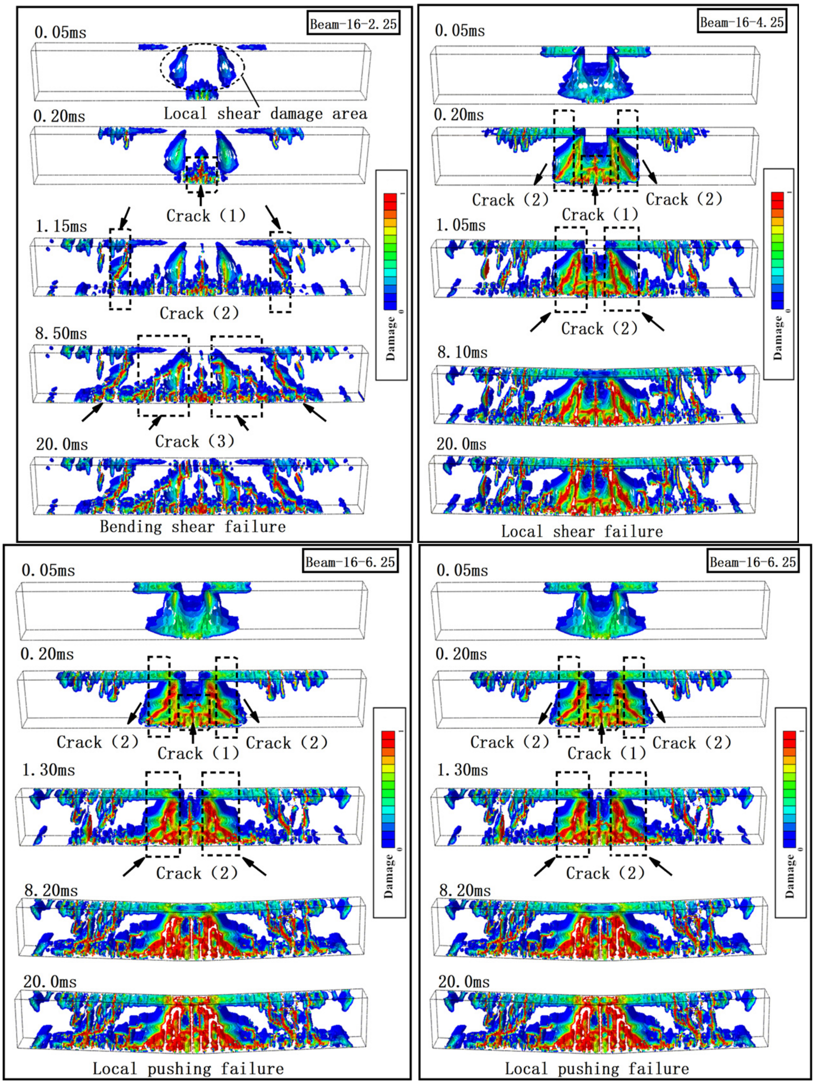
Table 4. Information on Specimens

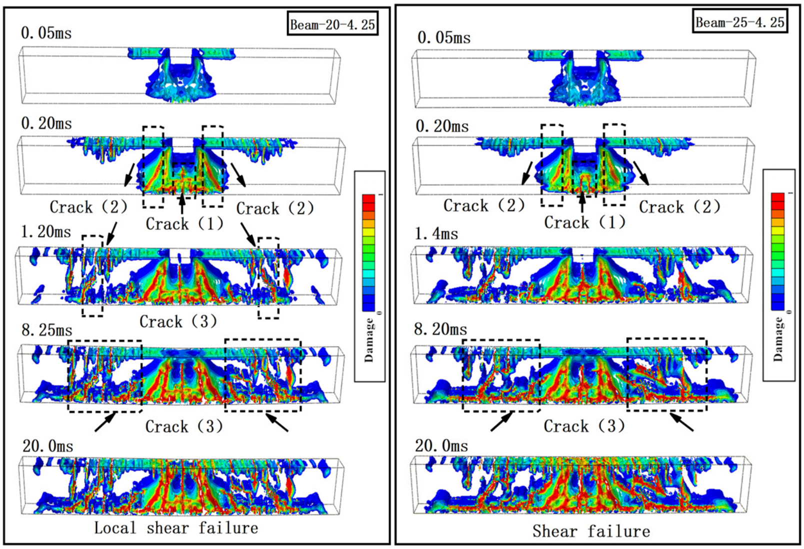
Specimen no.	Auxiliary bars	Bottom bars	Stirrup	Impact velocity (m/s)	Impact mass (kg)	V (N)	P (N·m)	V/P
Beam-16-2.25	2Φ10	2Φ12	φ8@150	2.25	400	166.74	50.616	1.85
Beam-16-4.25	2Φ10	2Φ16	φ8@150	4.25	400	166.74	89.985	1.85
Beam-16-6.25	2Φ10	2Φ18	φ8@150	6.25	400	166.74	89.985	1.85
Beam-20-4.25	2Φ10	2Φ16	φ8@150	4.25	400	166.74	89.985	1.22
Beam-25-4.25	2Φ10	2Φ25	φ8@150	4.25	400	166.74	136.41	0.86

It can be seen from Fig. 4 that the failure modes of the specimens in the overall response stage are quite different with the change of impact velocity and shear bending ratio, but there are obvious shear damage zones in the local response stage. Comparing the damage development time history of each specimen, study shows that the final RC beam with bending shear failure, such as Beam-16-2.25, the shear diagonal crack in the local area under the impact point extends from the bottom of the beam to the impact position. However, for RC beams with local shear failure, such as Beam-16-6.25 and Beam-20-4.25, the shear oblique cracks in the local area under the impact point start at the abdomen of the beam and extend to the bottom of the beam and the top of the beam respectively. This testifies that the abdominal shear type oblique crack is the characteristic of shear effect damage.

Impact velocity is the main factor affecting impact force and inertial force. By comparing the three beams Beam-16-2.25, Beam-16-4.25 and Beam-16-6.25, it shows clearly that the impact velocity increases from 2.45 m/s to 6.25 m/s, making the impact force and inertial force gradually increase, especially in the local response stage, which in turn causes an increase in the shear and bending moments experienced by the beam. In conclusion, the shear effect of the specimens in the local response stage becomes more and more obvious. If the designed shear resistance of the specimen is much greater than the shear force it is subjected to, the ultimate failure mode is similar to that under the condition of static load, both of which are mainly bending failure or bending shear failure, such as Beam-16-2.25; If the designed shear resistance of the specimen cannot resist the shear effect in the local response stage, the ultimate failure mode will change from local shear failure to punching shear failure with the increase of impact velocity, such as Beam-16-4.25 and Beam- 16-6.25, which is consistent with the research results of Zhao et al. [3] and Kishi et al. [5].

It can be concluded that great importance is supposed to be attached to the law of the dynamic internal force of the specimen in the local response stage when designing the impact bearing capacity of RC beams from the perspective of force. Shear bending ratio is a key factor in judging the bearing capacity of RC beams. The shear bending ratio is reduced from 1.85 to 0.86 by comparing the three beams Beam-16-4.25, Beam-20-4.25 and Beam-25-4.25. Although the bending resistance of the specimen gradually increases, the shear resistance remains unchanged. The shear force borne by the three beams all exceeds the designed shear resistance of the specimen, and the final failure mode is shearing damage. However, the enhancement of the bending resistance only makes the damage range of the specimen gradually increase, and the overall deformation coordination ability enhance, but it has little influence on the shear effect in the local response stage. Therefore, the final damage area of the three beams is still concentrated in the shear damage area just below the impact point. This manifests that analyzing the shear resistance of the specimen from the perspective of resistance is the key index for the impact resistance design of RC beams. It demonstrates that the beam first enters the local response stage before the stress wave reaches the supports at both ends of the beam at the initial moment of impact. Due to the extremely short duration, the beam often has no time to deform, with a 45°shear type damage area under the combined action of impact force and inertial force.


Beam-16-2.25
0.05ms
Local shear damage area
0.20ms
Crack (1)
1.15ms
Crack (2)
8.50ms
Crack (3)
20.0ms
Bending shear failure
Beam-16-4.25
0.05ms
0.20ms
Crack (2)
Crack (1)
Crack (2)
1.05ms
Crack (2)
8.10ms
20.0ms
Local shear failure
Damage
Beam-16-6.25
0.05ms
0.20ms
Crack (2)
Crack (1)
Crack (2)
1.30ms
Crack (2)
8.20ms
20.0ms
Local pushing failure
Beam-16-6.25
0.05ms
0.20ms
Crack (2)
Crack (1)
Crack (2)
1.30ms
Crack (2)
8.20ms
20.0ms
Local pushing failure
Damage



(Note: The arrow in the figure is the direction of crack development, and the number is the order in which the crack appeared)

Fig. 4. Damage Process Diagram

5 Conclusion

In this paper, the ABAQUS explicit dynamic module is used to establish a three-dimensional finite element model of a RC simply supported beam impacted by a drop weight, so as to study the impact resistance mechanical properties of the RC beam in the local response stage. Here draws the conclusion:

(1) The nonlinear dynamic response of RC beams under impact load can be divided into local response stage, overall response stage and deformational resilience stage. The shear effect is formed in the local response stage and fully developed in the overall response stage.

(2) With the change of impact velocity and shear bending ratio, the failure modes of the specimens in the total response stage differ apparently, but there are obvious shear damage zones in the local response stage. Meanwhile, when the shear resistance of the specimen remains unchanged, reducing the bending resistance of the specimen will not only cause the specimen to suffer from flexural damage, but also aggravate the shear failure of the specimen. However, increasing the bending resistance of the specimen is expected to enhance the overall deformation coordination ability of the specimen, thereby improving its impact resistance.

Acknowledgements

This work is supported by Science and Technology Project of China Road and Bridge Corporation with Grant No. P2220447, and also supported by Foundation of Xinjiang Institute of Engineering 2024 (Grant No. 2024xgy072605), by Science and Technology Planning Project of Sichuan Province with Grant No. 23ZDYF1911. The numerical calculations in this paper have been done on Hefei advanced computing center.

References

1. Zhang C., Gholipour G., Mousavi A A. Blast loads induced responses of RC structural members: State-of-the-art review[J]. Composites Part B: Engineering, 2020, 195: 108066.
2. Xu B., Zeng X.. Experimental study on the behaviors of reinforced concrete beams under impact loadings[J]. CHINA CIVIL ENGINEERING JOURNAL, 2014, 47(02): 41-51+61. (in Chinese)
3. Zhao D. , Yi W J, Kunnath S K. Shear mechanisms in reinforced concrete beams under impact loading[J]. Journal of Structural Engineering, 2017, 143(9): 04017089.
4. Tachibana S, Masuya H, Nakamura S. Performance based design of reinforced concrete beams under impact[J]. Natural Hazards and Earth System Sciences. 2010, 10(6): 1069-1078.
5. Kishi N, Mikami H. Empirical formulas for designing reinforced concrete beams under impact loading[J]. ACI Structural Journal, 2012, 109(4): 509-519.
6. ZHAO De-bo, YI Wei-jian. Anti-impact behavior and design method for RC beams[J]. JOURNAL OF VIBRATION AND SHOCK, 2014, 34(11): 139-145. (in Chinese)
7. Saatci S, Vecchio F. Effects of shear mechanisms on impact behavior of reinforced concrete beams[J]. ACI Structural Journal, 2009, 106(1): 78-86.
8. Pham T M, Hao H. Effect of the plastic hinge and boundary conditions on the impact behavior of reinforced concrete beams[J]. International Journal of Impact Engineering, 2017, 102: 74-85.
9. ZHAO Wuchao, QIAN Jiang. Study on Local Response Characteristics of RC Beams under Impact Loading[J]. Journal of Hunan University (Natural Sciences), 2014, 46(03): 25-32. (in Chinese)
10. Zhou X, Wang X, Zhang W, et al. Dynamic damage experiment and numerical simulation of stainless steel reinforced concrete beams[J]. Journal of Railway Science and Engineering, 2021, 18(09): 2400-2407.
11. Zhou X, Wang X, Zhang R, et al. An Experimental Study of the Effects of Different Reinforcement Ratios on the Impact Resistance Behaviors of Reinforced Concrete Beams[J]. Journal of Testing and Evaluation, 2020, 48(3): 2162-2184.