Research Article

Influence Factors Analysis of RC Beams under Falling Weight Impact Based on HJC Model

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Impact loads may cause serious or even fatal damage to the structure (component), in most existing specifications in China, and there are no special terms that take impact load into consideration. So, the response analysis of the structure (component) under impact loads is very important. In this paper, the sensitivity analysis was conducted for the 22 parameters of the Holmquist–Johnson concrete (HJC) constitutive model of concrete, and the sensitive parameters of the HJC model are identified with A , B , G , P_b , μ_b , and f_c respectively. LS-DYNA nonlinear transient finite element analysis code was used for this paper. Based on the validation of finite element modeling and choosing midspan deflection of RC beams and impact loads as response indices, some influencing factors on RC beams under falling weight impact were investigated, such as the mass and speed of falling weight, impact position, the strength of concrete and rebar, longitudinal reinforcement ratio, and the span of the beam.

1. Introduction

Impact is a kind of disaster, which is divided in direct menace, such as terrorist attacks and vehicle collision, and indirect menace caused by secondary disasters of traffic accidents and earthquakes. Thus, it can be seen that the threat of impact on the structure is increasing. In recent years, the problems of impact loads have been studied with the different methods. The dynamic property of concrete materials is an important factor to determine the accuracy of the structure using computer simulation, so the dynamic property of concrete materials is one of the key research topics. It is the strain-rate effect that causes the main differences between the dynamic and static properties of concrete materials, which refers to the phenomenon that higher mechanical behavior of the concrete with loading speed increasing [1]. The discovery of the effect means the beginning of the study of dynamic mechanical properties of concrete. Bischoff and Perry [2] summed up the early research results in this field and analyzed the relationship between the strain-rate effect of concrete and the increase coefficient of strength. Experimental method is the main way

to study the dynamic properties of concrete, and the hydraulic loading, falling weight impact loading device, split Hopkinson pressure bar (SHPB) loading, and plate impact loading are the popular ways for concrete fast loading. Comparisons of the four loading modes are listed in Table 1.

Some scholars have proposed the constitutive model which can be applied to the impact problem and verify the accuracy of the calculation: The element test of concrete constitutive model which is widely used in the finite element simulation of impact problem is carried out under various loading conditions by Tu and Lu, and the scope of application of the mode and the conditions of use are summarized; finite element simulation is carried out on an explosion shock problems, and the results show that the concrete damage model (MAT72) in the software LS-DYNA can fit well with the experimental results, and RHT in the AUTODYN also shows a good accuracy [7]. At the fourteenth international conference on missile, a strain rate dependent constitutive model-HJC model (MAT111), which is suitable for the simulation of highly nonlinear large deformation, is proposed by Holmquist and Johnson [8] and incorporated into the material library in LS-DYNA.

TABLE 1: Comparisons of the four ways.

Loading mode	Magnitude of strain rate	Scholar representative
Hydraulic loading	1 s^{-1}	Takeda and Tachikawa [3]
Falling weight impact loading	10 s^{-1}	Hughes and Gregory [4]
SHPB loading	$10 \sim 10^3 \text{ s}^{-1}$	Ross et al. [5]
Plate impact loading	$10^4 \sim 10^8 \text{ s}^{-1}$	Park et al. [6]

HJC model is one of the commonly used concrete constitutive models in the finite element analysis of impact, and its parameter values of the model are the key issues to be considered in the finite element modeling. However, the existing concrete HJC model has not been used in the parameter value table for all kinds of strength concrete, which has caused difficulty to the application of the model. In order to obtain accurate parameter values, it is necessary to test the properties of materials. However, the HJC model has 22 parameters, and determining all parameters is a large amount of work. Therefore, the sensitivity analysis was conducted for the HJC model parameters, which are divided into two categories, sensitive parameter (i.e., parameter changes will cause significant changes for the calculation results) and the nonsensitive parameter (i.e., parameter changes will not cause significant changes for the calculation results). In this way, when we adopt the model, the sensitive parameters can be determined by the experiment and the nonsensitive parameters can be determined by the HJC model, thus the test work in the parameter measurement will be greatly reduced.

There are two kinds of research methods on the impact problem about RC structure and member: experimental and numerical research. In the aspect of experiment, Kishi et al. [9] carried out the RC beam impact test considering size, reinforcement ratio, and speed of falling weight as the variables and impact force, supporting reaction, and mid-span deflection as the test objective, and the energy dissipation law and relationship of load-displacement curves were obtained for the high strength concrete beam under impact action, and Zhang et al. [10] found fracture energy and impact force peak of the member in direct proportion to the strain rate. Furthermore, there was a critical value of strain rate, and when the strain rate is less than that, the two peaks change slowly, otherwise, it would bring negative effects accordingly. Miao et al. [11, 12] presented a closed-form solution for the dynamic response of an infinite beam resting on a foundation considering the horizontal tangential effect under impact loads. Fujikake et al. [13] proposed a double-degree-of-freedom mass-spring-damper model to calculate the maximum midspan deflection, and maximum impact force as well the results of experiments and model calculations were in good agreement. In the aspect of computer simulation, Kishi et al. [14–16] applied LS-DYNA to establish the finite element model of RC beam about impact problem, and after calculation, the impact force, support force, displacement, and crack distribution were calculated and compared well with the experimental results. Abbas et al. [17] had established the finite element model of the RC beam about impact problem and compared the results obtained by the model simulation with the

experimental data, which verified the reliability of the finite element method. Material strain rate effect and the reinforcement of concrete constraints were considered, and the mechanical properties of RC beam subjected to axial force were simulated using LS-DYNA by Thilakarathna et al. [18]. Moreover, comparing the experimental data with the simulation results, the accuracy of the finite element model is proved, and the simplified model for calculating impact force and vulnerability assessment was developed.

The accuracy of the parameter values of the concrete material, which is generally obtained by experiments, has an important influence on the results of the impact simulation. *MAT_072 and *MAT_111 (HJC model) are suitable for low-speed impact problems. The *MAT_072 model can automatically generate material parameters, but the HJC model has no similar simplified model. In addition, the HJC model has 22 parameters, of which 18 parameters are related to the material properties, and when using the HJC model to simulate concrete, the determination of these 18 parameters is a heavy workload. If these 18 parameters can be distinguished as sensitive and nonsensitive parameters, the workload when determining the parameters can be reduced through the material performance experiment. In this paper, the modeling problem of RC beams based on HJC model is studied under falling weight impact. For the analysis results, the emphasis is on verifying the reliability with [19]. On this basis, the factors affecting the impact response of RC beams will be studied, such as the quality and speed of falling weight, impact position, the strength of concrete and rebar, and longitudinal reinforcement ratio.

2. Parameter Sensitivity Analysis of HJC Model

2.1. HJC Model. The HJC model is defined by *Mat_Johnson_Holmquist_Concrete in the K document of LS-DYNA, which has been recently widely used in the field of explosion, shock and other large deformation, and high strain rate. There are 22 parameters in the model, the results of which agree well with the experimental and simulation results.

16 of the 22 parameters can be divided into three categories:

- (1) Strength parameters: $A, B, C, N, G, S_{\max}$
- (2) Damage parameter: $D_1, D_2, \varepsilon_{f\min}$
- (3) Pressure parameter: $P_c, \mu_c, P_b, \mu_b, K_1, K_2, K_3$

The other 6 parameters are material number MID, density RO, compressive strength of concrete f_c , tensile strength of concrete T , strain rate $\dot{\varepsilon}_0$, and failure type f_s .

The HJC model is linear elastic before the failure of concrete. When the concrete yields, the damage starts to accumulate. When the concrete is completely out of failure, the stress state remains in the residual stress state.

By means of reducing the cohesive force on the initial failure surface, the strength of the material after yielding is obtained, and the initial failure surface is defined as

$$\begin{aligned}\sigma^* &= [A + BP^{*N}] \times (1 + C \ln \varepsilon^*), \quad \sigma^* \leq S_{\max}, \\ \sigma^* &= S_{\max}, \quad \sigma^* > S_{\max},\end{aligned}\quad (1)$$

where σ^* and P^* are normalized material strength and pressure, respectively, ε^* is the equivalent plastic strain rate normalized according to reference strain rate (1/s), A , B , N and C are material constants, and $S_{\max}$ is the material maximum strength value.

The yielding surface σ_{pf}^* of HJC model is defined as

$$\sigma_{pf}^* = [A(1 - D) + BP^{*N}] \times (1 + C \ln \varepsilon^*). \quad (2)$$

In Equation (2), the material damage index D is defined as

$$D = \int_0^{\varepsilon_p} \frac{d\varepsilon_p}{FS(P^*)}, \quad (3)$$

where $d\varepsilon_p = d\bar{\varepsilon}_p + d\mu_p$, $d\bar{\varepsilon}_p$, and $d\mu_p$ represent the equivalent plastic strain increment and the plastic volume strain increment, respectively, $FS(P^*)$ represents the cracking strain associated with hydrostatic pressure as follows:

$$\begin{aligned}FS(P^*) &= D_1 (P^* + T^*) D_2, \quad FS(P^*) \geq FS_{\min}, \\ FS(P^*) &= FS_{\min}, \quad FS(P^*) < FS_{\min},\end{aligned}\quad (4)$$

where uniaxial tensile strength of concrete in normalized compressive strength is used, D_1 and D_2 are the material parameters, and $FS_{\min}$ is the cut-off value of the minimum cracking strain.

In many concrete dynamic constitutive models, HJC model has been widely used worldwide because of its concise and reasonable description and the applicability of calculation procedures. Holmquist et al. proposed a set of parameters for the compressive strength of concrete (48 MPa) based on HJC model, which are listed in Table 2.

The set of parameters listed in Table 2 is only fit for the concrete of compressive strength $f_c = 48$ MPa. For other strength of concrete f_c , it is necessary to determine the parameter values of concrete by the material experiment, because HJC model has 18 parameters related to the mechanical properties, the experiment is a very large amount of work. In order to determine HJC model of the other strength of concrete, these parameters may be divided into sensitivity and nonsensitivity parameters. Thus, the main work of the following section is to conduct the parameter sensitivity analysis of HJC model.

2.2. Parameter Sensitivity Analysis of HJC Model. HJC model parameters are numerous, if simply rely on the experiment to obtain all the material parameters there are such as economic, time constraints. From the perspective of

engineering application, the sensitivity analysis of HJC model parameters is conducted, and then take different determination methods for different parameters, that is, make full use of existing experimental data and a small amount of material experiments to obtain the key parameters of HJC model. For specific engineering calculations, sensitivity parameter values should be carefully considered, the actual measurement should also improve the accuracy. Corresponds to the low sensitivity parameters, values may be determined according to references to meet calculation requirements and accuracy.

Besides using the original value in Table 2, the sensitive analysis needs to be conducted for the 18 parameter for HJC model. The paper employs four kinds of variable level, i.e., $\pm 20\%$ and $\pm 40\%$ [20]. The variable level of the objective function is extracted at the level of four levels and obtain the sensitivity parameter according to Equation (5). Moreover, the sensitivity analysis is carried out by the symmetric collision model (Figure 1), two cylinders complete a high speed collision by using HJC model. The peak displacement of the center node of the lower cylinder and the stress peak of intermediate section element are treated as the objective function, and the computational sensitivity values are obtained under various variable levels, the paper identify the sensitive parameters and summarize the influence trend of sensitive parameters. The process of parameter sensitivity analysis is shown in Figure 2.

The parameter sensitivity is defined as follows

$$S = \left| \frac{K(x_0 + d_i x_0) - K(x_0)}{K(x_0) \cdot d_i} \right|_{\max}, \quad (5)$$

where $K(x)$ represents the objective function, d_i the variable level $\pm 20\%$, $\pm 40\%$, x_0 represents the parameter values in Table 2.

There are 22 parameters in HJC model: 6 strength parameters: A , B , C , N , G , $S_{\max}$; 3 damage parameters: D_1 , D_2 , ε_{fmin} ; 7 pressure parameters: P_c , μ_c , P_b , μ_b , K_1 , K_2 , K_3 ; and the other 6 parameters: material number MID, density RO, compressive strength of concrete f_c , tensile strength of concrete T , strain rate $\dot{\varepsilon}_0$, failure type f_s . Material number MID, density RO, strain rate $\dot{\varepsilon}_0$, failure type f_s are not related to the mechanical properties of materials, so the sensitivity analysis is carried out only for the 18 parameters.

There are two objective functions for the sensitivity analysis: the peak displacement of the center node of the cylinder B# and the stress peak of intermediate section element. According to Equation (5), the sensitivity of each parameter is obtained in Table 3.

The method for determining a sensitive parameter is when there is an order of magnitude difference between displacement sensitivity value and maximum sensitivity value, it is determined that the parameter is a sensitivity parameter, and on the contrary, it is considered that the parameter is a nonsensitivity parameter. In Table 3, each of parameters has two sensitivity values, i.e., the displacement and stress, and the maximum sensitivity value of the displacement is 0.432, while that of the stress is 0.927. When any one of the two sensitivity values of a parameter reaches

TABLE 2: Parameter values of HJC model.

ρ_0 (kg/m ³)	G (Pa)	A	B	C	N	f_c (Pa)	T (Pa)	$\varepsilon_{f\min}$	$S_{\max}$	P_e (Pa)	μ_c	P_l (Pa)	μ_l	D_1	D_2	K_1 (Pa)	K_2 (Pa)	K_3 (Pa)	E (Pa)	$\dot{\varepsilon}_0$
2440	14.86E9	0.79	1.6	0.007	0.61	48E6	4.0E6	0.01	7.0	16.0E6	0.001	0.8E9	0.01	0.04	1.0	85.0E9	-171.0E9	208.0E9	35.7E9	1E-6

FIGURE 1: Scheme of numerical test for sensitivity analysis.

FIGURE 2: Dimension of RC beam.

TABLE 3: Parameters sensitivity of HJC model.

Parameter	A	B	C	N	G	$S_{\max}$	D_1	D_2	$\epsilon_{f\min}$	K_1	K_2	K_3	P_c	μ_c	P_l	μ_l	f_c	T
Displacement	0.169	0.132	0.016	0.037	0.432	0	0.006	0.003	0	0.022	0	0	0.007	0.008	0.056	0.057	0.381	0.002
Stress	0.431	0.927	0.097	0.075	0.154	0	0.086	0.032	0	0.030	0	0	0.096	0.087	0.263	0.226	0.871	0.013

the standard of the sensitivity parameter, it is determined that the parameter is sensitive.

According to the parameters in Table 3, we can determine that the sensitivity parameters are A , B , G , P_b , μ_b , and f_c . For these 6 parameters, if the researchers determine the parameters' value of their own, it is appropriate to carry out the detailed experiment, and the other 16 parameters can be determined according to Table 2.

3. Influence Factors Analysis of RC Beams under Falling Weight Impact

3.1. Finite Element Modeling and Verification. Kishi et al. studied the response of RC beams under 400 kg falling weight through the numerical and experimental research studies. Besides, the information of RC beam is shown in Figure 3 and Table 4. Using LS-DYNA software package, dynamic simulation analysis was carried out, and the results of the analysis are compared with [16], which verifies the reliability of the simulation analysis in this paper.

Furthermore, the analyses provide the reference for the further analysis of the impact response of reinforced concrete beams based on the HJC model.

The most widespread steel constitutive at present is Cowper–Symonds model and Johnson–Cook model [21]. Among them, the Cowper–Symonds model is applied to calculate the dynamic problems of low strain rate, while Johnson–Cook model is applied to calculate of the high strain rate dynamic problems. In this paper, because of the relative low strain rate, the Cowper–Symonds model is employed as follows:

$$\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/p}, \quad (6)$$

where $\dot{\epsilon}$ is the strain rate of steel, σ_d is the stress value at the strain rate $\dot{\epsilon}$, σ_s is the stress value of steel under static stress, D , and p represents the material parameters.

*MAT_003 constitutive model of the reinforcing steel bar was commonly used in LS-DYNA and can be obtained from the experiment of material properties. Because of the

FIGURE 3: Stress-strain relation of materials. (a) Main and shear rebars. (b) Concrete.

TABLE 4: Material information of RC beam.

Material	Strength (MPa)	Young's modulus (GPa)	Poisson ratio
Concrete	41.2	25.7	0.19
Axial rebar (D35)	373	206	0.3
Stirrup (D6)	373	206	0.3

absence of experiment data, the empirical value was applied, for example $D = 6844s - 1$, $p = 3.91$ [22–25]. The corresponding material parameters are shown in Table 5.

In Table 5, MID is the material ID, RO is the density of material, E the elastic modulus, PR is the Poisson ratio, SIGY is the yield strength, ETAN is the tangent modulus, BETA is the hardening parameter (0~1), SRC is similar to the D in Equation (6), SRP is similar to the p in Equation (6), FS is the failure strain, and VP is strain rate effect (0 or 1).

Compared with the *MAT_CONCRETE_DAMAGE of constitutive model of concrete, *MAT_CONCRETE_DAMAGE_REL3 has the simpler type and is easier to enter the parameters, and 3-card parameters are enough (Table 6), while the nonsimplified model needs to define 7-card parameters.

In Table 6, MID is the material ID, RO is the density of material, E the elastic modulus, PR is the Poisson ratio. A0 is the negative compressive strength, RSIZE is the conversion factor of length unit from inch to m, UCF is the conversion factor of pressure unit from psi to Pa, and LCRATE is the curve number of strain rate and dynamic enhancement factor.

Parameters LCRATE require a curve to express the relationship between the strain rate and the dynamic enhancement factor (i.e., a strain rate corresponding to a dynamic enhancement factor), listed in Table 7.

*MAT_003 constitutive model and element LINK160 are used for the reinforcing steel bar, and *MAT_CONCRETE_DAMAGE_REL3 and element SOLID164 are employed for concrete. The hourglass energy can be controlled by the refined mesh and the command *CONTROL_HOURLASS. The bonding between steel bar and concrete is treated by common node method. The stress and strain characteristics of concrete and reinforced steel bar used for the finite element analysis are shown in Figure 4. The material parameters of concrete and main rebar and

TABLE 5: *MAT_003 constitutive model of reinforcing steel bar.

Card 1	MID	RO	E	PR	SIGY	ETAN	BETA
	2	7800	$2.06e + 11$	0.3	$373e + 6$	$2.06e + 9$	0
Card 2	SRC	SRP	FS	VP			
	6844	3.91	0.2	0			

Note. The parameters in the table are set according to the international unit.

shear rebar are listed in Table 4. Steel falling weight, supporting apparatus, and anchor plate are modeled as elastic body. Young's modulus and Poisson's ratio are assumed as 206 GPa and 0.3, respectively. The finite element model is shown in Figure 5.

Kishi [15] studied the response of Type A RC beams subjected to a 400 kg falling weight impact by means of experiments and finite element analysis. The impact velocities were 4.6 m/s, 6.5 m/s, and 8.4 m/s, respectively. The impact force response and beam displacement in the mid-span were studied, the results are shown in Figures 5–7 (black dotted line for the finite element calculation results, the black solid line for the experiment results, and the blue solid line is analysis results in this paper).

In his paper, the same three kinds of impact velocity 4.6 m/s, 6.5 m/s, and 8.4 m/s are considered using LS-DYNA, and the impact force response and midspan displacement at Node 4130 are compared with Kishi [15] shown in Figures 5–7, respectively.

Compared the analysis results in this paper with the results of [19], it can be observed that time-history curves of the RC midspan displacement are almost the same on the overall trend of the curve, and the peak values agree well with [17] (including the experimental value and finite element calculation); there is about 5% error, and the residual displacement is also similar. It can be considered that the midspan displacement of RC beam is in good agreement with [19]. About the impact force response, it can be

TABLE 6: *MAT_CONCRETE_DAMAGE_REL3 constitutive model of concrete.

Card 1	MID 72	RO 2.4E + 03	PR 0.19					
Card 2	FT —	A0 -41.2 + 06	A1 —	A2 —	B1 —	OMEGA —	A1F —	
Card 3	SL —	NOUT —	EDROP —	RSIZE 39.4	UCF 145.0	LCRATE 723	LOCWID —	NPTS —

Note. For the simplified model, the vacant parameters in the table need not be defined (nonsimplified mode needs).

observed that time-history curves of the impact force are almost similar to [19], and the trend of curves is a pulse followed by a few decaying oscillations. The error of maximum impact force values is within 10%.

By adding the keyword word *MAT_ADD_EROSION and setting the appropriate failure criteria, cracks in reinforced concrete beam can be viewed. The strain control failure is employed, and the failure strain is set to 0.003. Through the calculation, the cracking state of the RC beam can be obtained as shown in Figure 8.

From Figure 8, it can be found that the bottom of the cross section of RC beam emerges tensile fracture due to the bending moment, serious shear cracking occurs in the whole span, and the shear fracture extends from the top of the impact part to the bottom of the support section. Figure 9 is the crack of A type beam subjected to 400 kg falling weight impact experiment at the speed 4.6 m/s in [25]. By comparing Figures 8 and 9, we can find that the crack patterns of the two are similar, which further confirms the correctness of modeling.

3.2. Analysis of Influencing Factors. Because there are many factors affecting the impact response of reinforced concrete beams, the parametric modeling method is adopted. On the one hand, in the design of the beam, the span, section size, and reinforcement of the beam are shown in Figure 3, and the mechanical properties of the steel and concrete are shown in Table 4. On the other hand, the mass of falling weight is 400 kg, and speed is 6 m/s. Finally, the boundary conditions of RC beam are fixed at both ends. Some influence factors (strength of concrete, ratio of longitudinal reinforcement, length of beam span, impact location, mass of falling weight, and impact speed) will be discussed based on the HJC model.

3.2.1. Effect on Strength of Concrete. Firstly in the category of statics, strength of concrete is an important index of the performance of reinforced concrete beams. Therefore, it is interesting in studying the influence of the strength of concrete on the dynamic response. Secondly, through the parameter sensitivity analysis of HJC model, 6 sensitivity parameters are identified: A , B , G , P_b , μ_b , and f_c . A , B , G , and f_c belong to the strength parameters, while P_l and μ_l belong to the pressure parameters. Thirdly, the numerical experiment of different strength concrete ($f_c = 38, 40$, and 48 MPa) is carried out in this paper. The sensitivity parameters are shown in Table 8. The other nonsensitivity parameter values are determined according to Table 2.

After determining the parameters of three kinds of concrete with different strength, the strength influence on the impact response analysis is carried out for the reinforced concrete beam under falling weight impact. Response comparisons of the midspan displacement and impact force of RC beam are shown in Figure 10.

As shown in Figure 10(a), there are little differences in the response of midspan displacement of the RC beam. Moreover, when the strength of concrete changes from 33 MPa to 48 MPa, the peak value of midspan displacement declines from 17 mm to about 14 mm, for which the variation range is less than 20%, and the displacement oscillation section, which is referred as the remaining part after the peak displacement, changes very little. As shown in Figure 10(b), the time-history curves' impact force for three kinds of concrete is almost completely coincident, and the variation range is less than 5%. Besides, the duration and peak value of the impact force oscillation section also nearly coincide.

Comparison results show that the variation of concrete strength which ranges from 30 MPa to 50 MPa has a little influence on the displacement response of RC impact beams, but the influence on the impact force response is smaller.

3.2.2. Effect on Ratio of Longitudinal Reinforcement. Three kinds of diameters of the longitudinal reinforcement bar ($\Phi 20$, $\Phi 24$, and $\Phi 28$) are selected to conduct the comparison analysis, combined with the cross section size shows that the reinforcement ratio of the reinforced concrete is 0.0118, 0.0170, and 0.231, respectively.

The impact response of the RC beam is obtained under falling weight impact. The comparisons of midspan displacement and impact force are compared under three kinds of longitudinal reinforcement ratios as shown in Figure 11.

As shown in Figure 11(a), it can be found that there is a great difference in the response of midspan displacement for the RC beams with different ratios of longitudinal reinforcement. With the increase of ratios of longitudinal reinforcement, the midspan displacement effectively decreases. When the ratio of longitudinal reinforcement increases from 1.18% to 2.31%, the peak midspan displacement response decreases by more than half, and the displacement of the oscillation segment also decreases significantly. Moreover, as shown in Figure 11(b), the impact force response of the RC beams with different ratios of longitudinal reinforcement is also greatly affected, for which the maximum impact force increases by about 40% when the ratios change from 1.18% to 2.31%. The value of oscillation

FIGURE 4: Impact response comparisons of RC beam at the speed 4.6 m/s. (a) Time-history curve of midspan displacement. (b) Time-history curve of impact force.

FIGURE 5: Finite element model of RC beam. (a) Concrete element. (b) Reinforcement element.

FIGURE 6: Impact response comparisons of RC beam at the speed 6.5 m/s. (a) Time-history curve of midspan displacement. (b) Time-history curve of impact force.

segment also increases accordingly but the oscillating time is relatively shorter.

The comparison results show that the reinforcement ratio is an important factor for the impact response of the RC beam, and it has great influence on the response of midspan displacement and the impact force.

3.2.3. Effect on Length of Beam Span. The four kinds of length of beam span (2.0 m, 2.4 m, 2.8 m, and 3.2 m) are considered. The corresponding comparisons of midspan displacement and impact force are shown in Figure 12.

From the comparison of Figure 12(a), it can be found that there is a great difference in the midspan displacement

FIGURE 7: Impact response comparisons of RC beam at the speed 8.4 m/s. (a) Time-history curve of midspan displacement. (b) Time-history curve of impact force.

FIGURE 8: Crack pattern of RC beam simulation (LS-DYNA).

FIGURE 9: Crack pattern of RC beam experiment [15].

TABLE 8: Sensitivity parameters of three kinds of concrete strength.

Concrete strength (MPa)	A	B	G (GPa)	f_c (MPa)
48	0.79	1.60	14.86	48
40	0.53	1.73	13.69	40
33	0.27	1.86	12.53	33

response of the RC beam with different lengths of beam span. With the increase of the span length, the midspan displacement increases sharply, and when the span length changes from 2.0 m to 3.2 m, the midspan displacement increases by more than two times. Especially for 3.2 m span length, it can be seen that the midspan displacement reaches the maximum value and no longer recovers, which indicates that the concrete damage is more serious. As shown in Figure 12(b), the impact force responses of the RC beam

with different span lengths are also greatly affected, and the maximum impact force response decreases with the increase of span length. For example, the maximum impact force declines by about 30% when the span length increases from 2.0 m to 3.2 m. And the oscillation segment also tends to be gentle, while the response time is relatively prolonged. The comparison results show that the lengths of beam span is an important factor for the response of the midspan displacement and the impact force of RC beam.

3.2.4. Effect on Impact Position. The impact position of the model is in the midspan of the beam (1/2), and the other three impact positions are considered as 3/8, 1/4, and 1/8 of the beam span. The corresponding comparisons of midspan displacement and impact force are shown in Figure 13 under falling weight impact.

FIGURE 10: Comparison of impact response of different concrete strengths. (a) Comparison of midspan displacement. (b) Comparison of impact force.

FIGURE 11: Comparison of impact response of different ratios of longitudinal reinforcement. (a) Comparison of midspan displacement. (b) Comparison of impact force.

As can be seen from the comparison of Figure 13(a), when the same RC beam is subjected to impact at different positions, there is a significant difference in the displacement response immediately below the impact point. When the impact position moves closer and closer to the support point (or away from midspan of the beam), the midspan displacement decreases obviously. For example, when the impact position moves from 1/2 to 1/8 span, the displacement decreases more than 40%, and the displacement of the oscillation segment decreases. When the impact

location moves to 1/8 span, it can be observed that there is a significant fluctuation in the oscillation segment after the peak displacement, which indicates that the beam has very good elasticity and its damage is very little. Figure 13(b) indicates that the maximum impact force is almost unaffected when the RC is subjected to falling weight impact at different impact positions. And as the impact position becomes closer to the support of the beam, oscillation time is longer and the magnitude increases after the peak oscillation.

FIGURE 12: Comparison of impact response of different lengths of beam span. (a) Comparison of midspan displacement. (b) Comparison of impact force.

FIGURE 13: Comparison of impact response of different impact position. (a) Comparison of midspan displacement. (b) Comparison of impact force.

The results show that the impact position has a great influence on the response of midspan displacement and obvious effect on the oscillation segment.

3.2.5. Effect on Mass and Speed of Falling Weight. The mass and speed of the falling weight is usually used to measure the impact strength and another two physical quantities, impulse and kinetic energy, and can also be used to measure the impact strength. To explore the four factors' effect on the concrete beam impact response, this section will design nine groups of working condition with mass and velocity. The nine sets of working conditions are shown in Table 9.

To calculate the working conditions of the 9 speed and quality combination, the results of the simulation are compared with the results in the following four ways.

The comparison of 1, 2, 3, and 4 working conditions is shown in Figure 14. On the one hand, the deflection response has significant differences, for which the deflection increases obviously with the increase of falling mass. For instance, with the quality of hammer increasing from 400 kg to 700 kg, the deflection grows more than 60 percent and the value of oscillation section deflection increases, meaning that beam is subjected to damage. On the one hand, as is shown in Figure 14(b), when the RC beam is impacted in different quality, the peak value of the impact force is almost

TABLE 9: Combination of mass and speed of falling weight.

Case	Number of beam	Mass (kg)	Speed (m/s)	Impulse (kg·m/s)	Kinetic energy (J)
1	B4600	400	6.00	2400	7200
2	B5600	500	6.00	3000	9000
3	B6600	600	6.00	3600	10800
4	B7600	700	6.00	4200	12600
5	B6400	600	4.00	2400	4800
6	B6490	600	4.90	2940	7203
7	B6700	600	7.00	4200	14700
8	B8300	800	3.00	2400	3600
9	B8424	800	4.24	2292	7191

FIGURE 14: Comparison of impact response (constant speed and variable quality). (a) Comparison of midspan displacement. (b) Comparison of impact force.

not affected, but the oscillation time is prolonged, and the amplitude decreases after the peak.

The comparison results show that the quality of the hammer is an important factor for the impact response. It has a great influence on the response of deflection and obvious effect on the oscillation section.

The comparison of 3, 5, 6, and 7 working conditions is shown in Figure 15. On the one hand, the deflection response has significant differences, for which the deflection increases obviously with the speed increases. For instance, with the speed of hammer increasing from 4 m/s to 7 m/s, the peak value increases by more than 1 times, and the value of oscillation section deflection increases, meaning that beam is subjected to damage. On the other hand, as is shown in Figure 15(b), when the RC beam is impacted in different speed, the peak value of the impact force has a significant increase, and the oscillation time is prolonged and the amplitude increases after the peak.

The comparison results show that the speed of hammer is an important factor for the impact response, which has significant influence on the deflection response and the impact force response.

As is shown in Figure 16(a), the same impulse is not guaranteed in the same deflection response, which is conducted on working conditions 1, 5, and 8. Besides, the difference between B4600 and B8300 in the peak value of midspan deflection is about one times, and the difference of the amplitude of the oscillation is very large too. From the point of view of kinetic energy, the greater the kinetic energy of the working conditions, the greater the deflection response in constant impulse.

As is shown in Figure 16(b), the same impulse is not guaranteed in the same impact response. For example, the amplitude of the beam B8300 is up to about 80% relative to the beam B4600. According to the momentum theorem, the area of the three impact force time-history curves should be equal, which means the peak value is inversely proportional to the duration, proved in the $B4600 > B6400 > B8300$ in Figure 16(b). It can be concluded that when the impulse is the same, the greater kinetic energy in the working condition will lead to greater impact force response, but the corresponding impact force duration tends to be short.

As is shown in Figure 17(a), we can find that there is only slight difference between the three beams in the midspan

FIGURE 15: Comparison of impact response (constant quality and variable speed). (a) Comparison of midspan displacement. (b) Comparison of impact force.

FIGURE 16: Comparison of impact response (constant impulse). (a) Comparison of midspan displacement. (b) Comparison of impact force.

deflection curve, for which the difference of the deflection is within 10%. Accordingly, we consider that when the other conditions are the same, the kinetic energy of the falling weight impact is a measure and reference index in midspan deflection, meaning that if the hammer has the same kinetic energy, it will have a deflection impact response of similar or even the same peak.

As is shown in Figure 17(b), the peak value of the impact force has a greater change in amplitude than the deflection value. For example, the amplitude of the beam B8424 is down to about 20% relative to the beam B4600. According to the view of momentum, it can be concluded that when the kinetic energy is the same, the smaller impulse in the

working condition will lead to greater impact force response, which does not match the initial guess of the researchers. But the area of the B8424 impact force curve is larger than that of B4600, which shows that the actual condition is consistent with the theory of momentum.

4. Conclusion

The sensitivity analysis was conducted for the 22 parameters of the Holmquist–Johnson concrete (HJC) constitutive model of concrete. Based on the validation of finite element modeling and choosing midspan deflection of RC beams and impact loads as index of response, some influencing factors

FIGURE 17: Comparison of impact response (constant kinetic energy). (a) Comparison of midspan displacement. (b) Comparison of impact force.

on RC beams under falling weight impact were investigated using LS-DYNA nonlinear transient finite element analysis. The results obtained from this study are as follows:

- (1) The 6 sensitivity parameters of concrete HJC constitutive model are A , B , G , P_b , μ_l , and f_c . At the same time, it should be noted that if the selection of the objective function is not the same, the results of parameter sensitivity analysis might not be the same. When the peak deflection of the impact surface is selected as the target function, the P_l and μ_l are not sensitive parameters, but when the stress of the middle element of the impact body is selected as the target function, the two parameters are sensitive.
- (2) The obvious factors influencing the response of the midspan displacement are the ratio of longitudinal reinforcement, beam span, impact location, mass, and speed of falling weight impact. The obvious factors influencing the response of the impact force are the ratio of longitudinal reinforcement, beam span, impact position, and speed of falling weight impact.
- (3) There are two methods to determine the influence of a factor on the midspan deflection: the first is to judge whether it has influence on the rigidity, like beam span and impact point position, the deflection decreases with the stiffness increases; the second is to judge whether it has influence on the kinetic energy, like speed and quality of the hammer, the deflection increases with the kinetic energy increases. Lastly, stiffness is the main basis to determine whether a factor has no effect on the deflection of the middle span.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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