Analysis of Impact Response of Reinforced Concrete Columns under Horizontal Impact Load

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***Abstract*—Reinforced concrete columns are important members of the structure. Therefore, it is necessary to study the impact response of RC columns under impact load, and correctly understand the performance and performance of RC columns under horizontal impact loads and provide reference for the improvement of reinforced concrete columns impact design. The RC columns finite element model was established by ANSYS/LS-DYNA software and the eight factors of RC columns under horizontal impact load was discussed. The results show that the impact response is mainly affected by the impact energy and the local or overall stiffness of the RC column.**

***Index Terms*—reinforced concrete column; impact load; analysis of impact response**

I. Introduction

The existing building structure is mainly reinforced concrete structure, and the building structure is inevitably subjected to various dynamic loads during its use, such as impacts on structures such as cars, airplanes, ships, falling rocks, explosions of terrorist incidents, etc. [1-3]. In the above various impact loads, especially in the case of medium and low speed collisions of piers and columns, such as automobiles and ships, it occurs more frequently. Therefore, research on the dynamic response of reinforced concrete columns under impact loads has become particularly important, it can not only improve the impact resistance of the column, but also reduce the damage of components and structures. Many scholars have also made a lot of research: Japanese scholar Kishi N [4-9] studied the impact resistance of reinforced concrete beams under medium and low speed impact loads by means of a large number of drop hammer impact tests and numerical analysis. Ožbolt J., Sharma A. [10] studied the performance of reinforced concrete beams strengthened with different shear conditions under dynamic impact loads by numerical simulation. Fujikake K., Li B., Soeun S. [11] using the method of drop weight test and theoretical analysis to show that the improvement of longitudinal reinforcement ratio can enhance the impact resistance of reinforced concrete beams. Mohammed T. A. [12] used three-dimensional complex nonlinear finite element analysis to study the application of CFRP-composite sheets and honeycomb cellular structure to reduce the damages to the structural members caused by impact loading.

The constitutive relationship of the concrete used in this paper under dynamic loading is the formula given by the European Concrete Association-International Structured Concrete Association (CEB-FIB) specification [13]. The reference model of reinforced concrete column is established by ANSYS/LS-DYNA software [14,15], and by changing one of the single variables, the effects of various factors on the column impact response are explored, and the data are systematically analyzed to obtain reliable conclusions.

II. Merical Analysis Model

A. Model Establishment

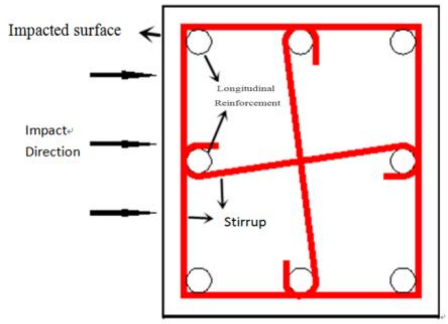
The finite element model of the reinforced concrete column established by ANSYS/LS-DYNA software is shown in Figure1. In order to set the boundary conditions of the finite element model of the concrete column and apply the axial load, rigid blocks are placed at both ends of the concrete column. Upper parts of concrete column constrain horizontal displacement degrees of freedom and all rotational degrees of freedom, lower parts of concrete column are used to restrain all displacement and rotational freedom; the reinforced concrete column is subjected to the impact of a rigid cylinder perpendicular to the impact plane (The model uses the MAT_RIGID rigid body model and does not consider the deformation of the impact body) (Figure 1a,b). The parameters in the model are defined as follows: the contact plane between the impact block and the concrete column is the impact surface, and the plane on the opposite side is the back impact plane (see Figure 1a); section size: b (section width) × h (section height), column height H (see Figure 1b); the initial position of the bottom surface of the impact cylinder is 3 mm apart from the impact plane, the impact height Hc is the vertical height of the cylinder axis from the top surface of the concrete column bottom (see Figure 1b).The cell grid size is set to 20 mm and the solution end time is set to 100 ms.

Table 1. Summary of the finite element model of the main materials and parameters.

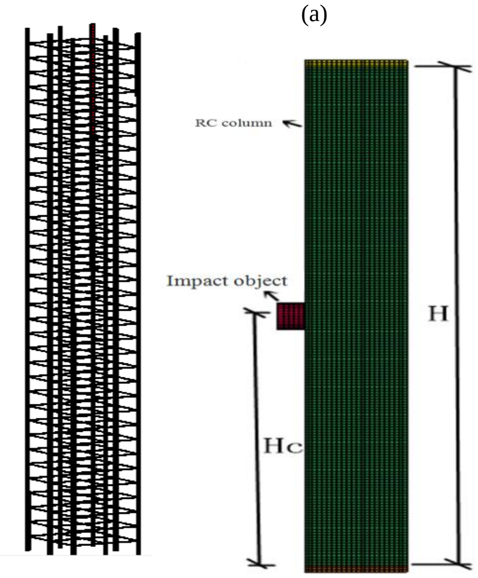
Part	Material model	Intensity (MPa)	Density (kg/m^3)	Poisson ratio	Modulus (GPa)	Reinforcement unit failure strain
Longitudinal steel	Mat_ plastic_	Fy = 400 MPa	7800	0.3	E = 206	0.12

Part	Material model	Intensity (MPa)	Density (kg/m^3)	Poisson ratio	Modulus (GPa)	Reinforcement unit failure strain
bar	kinematic				Et = 2.06	
Stirrup	Mat_ plastic_ kinematic	Fy = 300 MPa	7800	0.3	E = 206	0.12
					Et = 2.06	
Concrete	Mat_ CSCM	Fc = 30 MPa	2400	0.2	--	--

Fc = Concrete strength, Fy = Yield strength, E = Elastic modulus, Et = Tangent modulus.



(a)



(b) (c)

Figure 1. Schematic diagram of section size and finite element model of RC columns: (a) Section size; (b) Reinforced model; (c) Impact model.

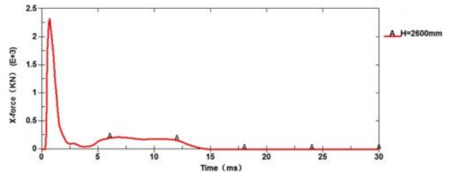
B. Parameters of the Benchmark Model

In order to facilitate the description of the changes of different parameters, the benchmark model of the following dimensions is first established: the height of the reinforced concrete column is H = 3.6 m, and the section size is b × h = 400 mm × 450 mm. Concrete strength grade: C30, concrete cover thickness 30mm, longitudinal reinforcement with 8 diameter HRB400 grade steel bars ; the stirrups are made of HPB300 grade steel bars with a spacing of 100 mm and a diameter of 8mm (Φ8@100), the impact block is located at Hc = H/2, the mass of the block is 600 kg, and the initial impact velocity is set to 11 m/s; the research in this paper is realized by changing some of the above parameters. The other parameters of the benchmark model are shown in Table 1.

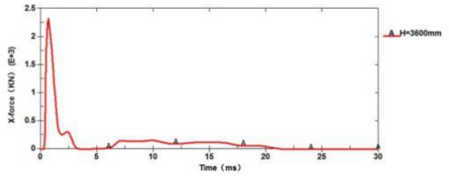
III. Result Analysis and Discussion

A. Column Height

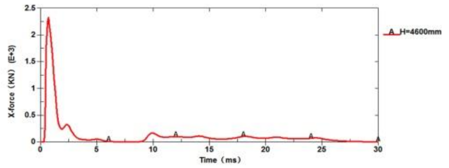
In this paper, the reinforced concrete columns with column heights of H = 2.6 m, H = 3.6 m and H = 4.6 m are selected for analysis. The other parameters of the model are consistent with the settings of the benchmark study. The impact force time curve is shown in Figure 2.



(a) H = 2600 mm



(b) H = 3600 mm



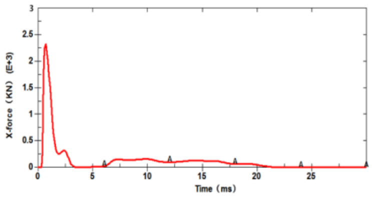
(c) H = 4600 mm

Figure 2. Impact force time curve.

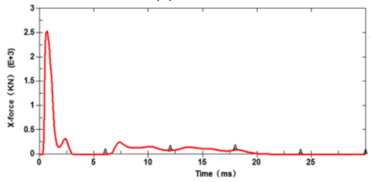
Comparing the different Impact force time curve in the comparison chart, it can be seen that the impact forces at three different column heights reach the maximum value at around 0. 699 ms, and the maximum values are almost the same, when the column height is increased from 2600 mm to 4600 mm, the oscillation duration is increased from 12.5 ms to 23.7 ms, a total increase of 89.60%. In summary, the change in column height has less effect on the maximum impact force. Before entering the shock oscillation phase, the trend of the three curves is basically the same, and in the shock oscillation phase after the peak, the oscillation duration increases significantly with the increase of the column height, and the oscillation fluctuation amplitude gradually becomes gentle.

B. Concrete Strength

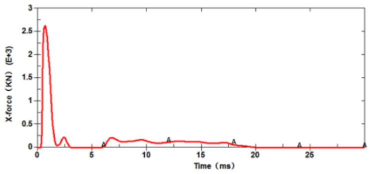
In this paper, the dynamic response of reinforced concrete columns of three different concrete strength grades (C30, C40, C50) is studied by changing the value of concrete axial compressive strength in the benchmark model. The other parameters of the model are consistent with the settings of the benchmark study. The impact force time curve is shown in Figure 3.



(a) C30



(b) C40



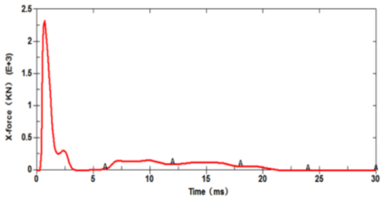
(c) C50

Figure 3. Impact force time curve.

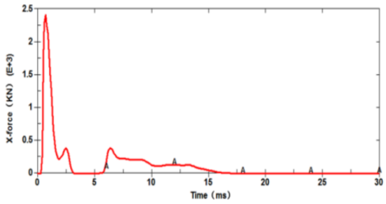
The comparison found that the impact strengths of the three concrete strength specimens of C30, C40 and C50 are 2332 KN, 2546 KN and 2638 KN, respectively; the peak impact force of C40 and C50 concrete grades is 9.17% and 13.12% higher than that of C30 concrete grade; during the oscillation phase, the trend of the three operating conditions and the oscillation duration are almost identical. Therefore, the difference in the compressive strength level of the concrete shaft only affects the maximum peak value of the impact force, but has little effect on the fluctuation amplitude and oscillation duration of the impact force oscillation phase.

C. *Axial Pressure Ratio* (*μ*)

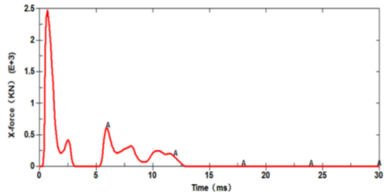
In this paper, the influence of axial pressure ratio (μ) on the dynamic response of reinforced concrete columns is studied by applying different axial pressures on the top of concrete columns. The impact force time curve is shown in Figure 4.



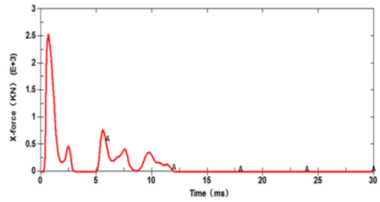
(a) μ = 0.00



(b) μ = 0.15



(c) μ = 0.30



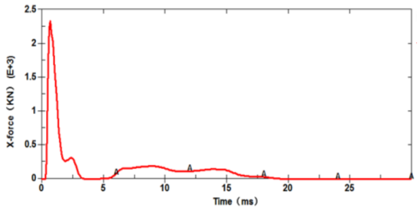
(d) μ = 0.45

Figure 4. Impact force time curve.

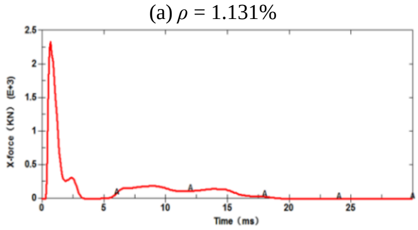
The impact force time curve of the four different axial pressure ratios in Figure 4 shows that the maximum peak impact is increased by 13.12% when the axial pressure ratio is increased from μ = 0.00 to μ = 0.45. As the axial pressure ratio increases, the peak impact force increases slowly, the fluctuation frequency of the oscillation phase increases, and the overall oscillation duration becomes shorter.

D. *Longitudinal Reinforcement Ratio*

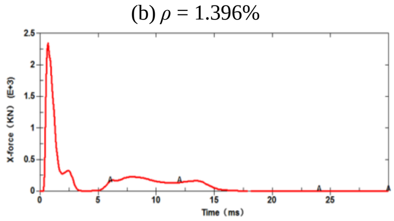
Study the effect of the longitudinal reinforcement ratio on the dynamic response of reinforced concrete columns by changing only the longitudinal reinforcement diameter in the reference example. Select reinforced concrete columns with four different longitudinal reinforcements (the dimensions are 18 mm, 20 mm, 22 mm, 25 mm, and the corresponding longitudinal reinforcement ratios are: ρ = 1.131%, ρ = 1.396%, ρ = 1.689%, ρ = 2.181%) for analysis. The impact force time curve is shown in Figure 5.



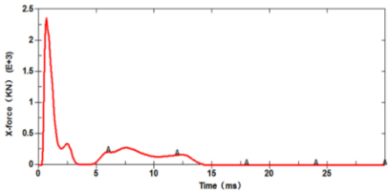
(a) ρ = 1.131%



(b) ρ = 1.396%



(c) ρ = 1.689%



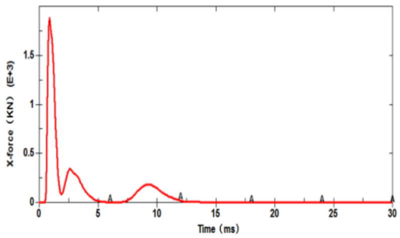
(d) ρ = 2.181%

Figure 5. Impact force time curve.

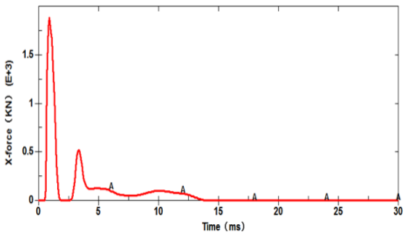
Comparing the impact force time curve of different longitudinal reinforcement ratios in Figure 5, the maximum impact force of the four different reinforcement ratio conditions is about 2330 KN. Therefore, the change in the reinforcement ratio of the longitudinal reinforcement does not have a significant effect on the peak impact force. The amplitude of the impact force in the oscillation phase increases with the increase of the longitudinal reinforcement ratio, but the duration of the shock oscillation is shortened.

E. Impact Position

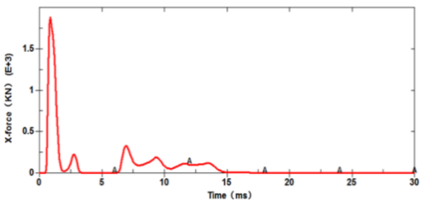
In this paper, three kinds of impact positions (Hc = H/4, Hc = 3H/4 and Hc = H/2) are selected to analyze the impact response of reinforced concrete columns, the initial impact velocity of the impact block is set to 7 m/s. The impact force time curve is shown in Figure 6.



(a) Hc = H/4



(b) Hc = 3H/4



(c) Hc = H/2

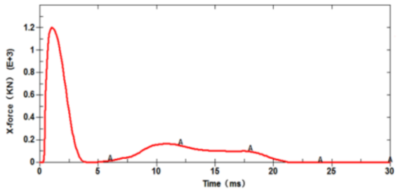
Figure 6. Impact force time curve.

The curves are roughly the same, immediately after the impact block contacts the cylinder, the impact force rapidly rises to the maximum peak value in a very short time, and then rapidly drops to form the largest triangular pulse region in the impact force time curve; thereafter, the impact force produces an impact oscillation phase of different fluctuation forms, which ends until the impact mass and the cylinder rebound and separate, and the end sign is that the impact force drops to zero and does not change.

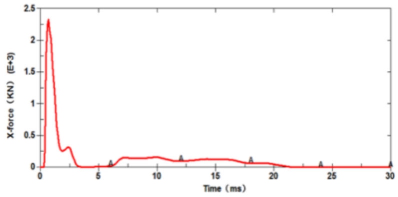
It can be seen that the maximum peak value and peak value of the impact force under three conditions are almost the same; in the shock oscillation phase after the maximum peak, the oscillation fluctuation frequency is most significant when the operating condition Hc = H⁄2, and the oscillation duration is the longest; in the oscillation phase of the working condition Hc = 3H⁄4, only one short-term fluctuation occurs, and in the oscillation phase of the working condition Hc = H⁄4, two significant fluctuations occur and the fluctuation oscillation lasts for a long time. The comparison shows that the difference of the impact load position has a significant influence on the wave form of the shock oscillation phase and the overall duration of the oscillation, but has little effect on the maximum peak of the impact force.

F. Impact Contact Area

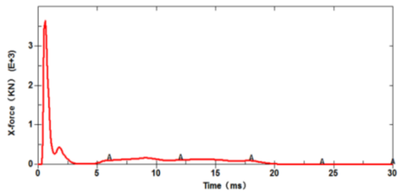
In this paper, four kinds of cylinders with bottom diameters of D = 100 mm, 200 mm, 300 mm and 400 mm are selected for impact loading of reinforced concrete columns, and the density of impact objects is consistent. The impact force time curve is shown in Figure 7.



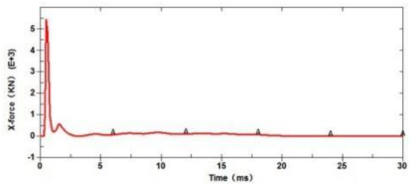
(a) D = 100 mm



(b) D = 200 mm



(c) D = 300 mm



(d) D = 400 mm

Figure 7. Impact force time curve.

Comparing the impact force time curve of different impact object diameter examples in Figure 7, it is found that: the peak impact force increased from 1202.3 KN at D = 100 mm to 5457.1 KN at D = 400 mm, with a growth rate of 353.89%, and the shock oscillation time was between 5 ms and 20 ms. It can be seen that as the diameter of the impact object increases, the impact contact area increases, resulting in a significantly increasing peak of the impact force, but the oscillation is almost consistent.

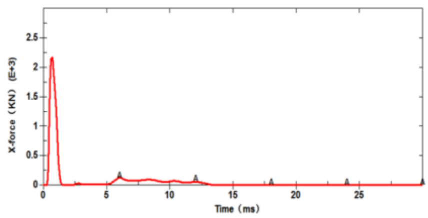
G. Impact Mass and Impact Velocity

Passing 5 different working conditions (see Table 2), in the case of maintaining the same increase in impact kinetic energy, two factors (impact quality, impact velocity) were changed to study its effect on the dynamic response of reinforced concrete columns. The impact force time curve is shown in Figure 8.

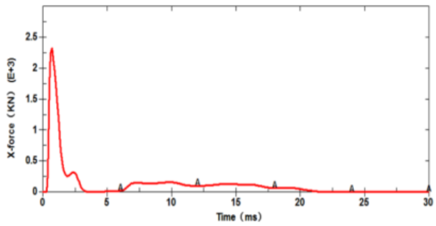
Table 2. Design table of impact velocity and mass change.

Number	Mass (kg)	Velocity (m/s)	Kinetic energy (J)
C30011	300	11	18150
C60011	600	11	36300
C90011	900	11	54450
C60007	600	7.778	18149.2 (about 18150)
C60013	600	13.470	54432.3 (about54450)

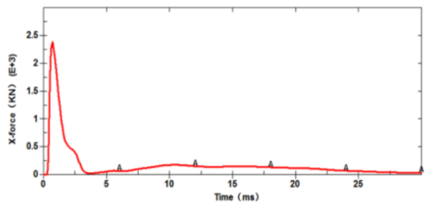
The number C represents the reinforced concrete column; the first three digits of the five digits represent the mass of the impact mass, the unit is: kg; the last two digits are the speed code.



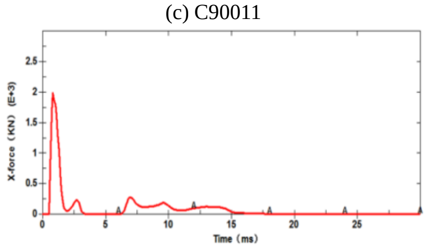
(a) C30011



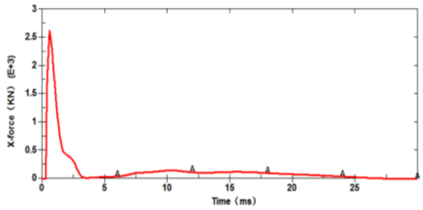
(b) C60011



(c) C90011



(d) C60007



(e) C60013

Figure 8. Impact force time curve.

Compare Figure 8a,b,c; analysis of the impact force time curve of the three test pieces shows that the impact peaks of the three working conditions of C30011, C60011 and C90011 are 2167.3KN, 2332.8KN and 2389.7KN, the duration of the shock oscillation is 11.8 ms, 19.3 ms and 26.5 ms, C60011 has a 7.64% higher impact force peak and a 63.56% longer oscillation duration than C30011; C90011 has a 2.44% higher impact peak and 37.31% longer oscillation duration than C60011. It can be concluded that when the impact velocity is the same, as the impact mass increases, the peak value of the impact force increases and the duration of the shock oscillation is significantly prolonged.

Compare Figure 8a,b,c; analysis of the impact force time curve of the three test pieces shows that the impact peaks of the three working conditions of C30011, C60011 and C90011 are 2167.3 KN, 2332.8 KN and 2389.7 KN, the duration of the shock oscillation is 11.8 ms, 19.3 ms and 26.5 ms, C60011 has a 7.64% higher impact force peak and a 63.56% longer oscillation duration than C30011; C90011 has a 2.44% higher impact peak and 37.31% longer oscillation duration than C60011. It can be concluded that when the impact velocity is the same, as the impact mass increases, the peak value of the impact force increases and the duration of the shock oscillation is significantly prolonged.

In summary, it is found that the influence of the two factors on the peak impact force and the impact oscillation time is different: the more significant factor affecting the peak impact force is the impact velocity and the more significant factor affecting the duration of the shock oscillation is the impact mass.

IV. Conclusions

In this paper, the impact force response of reinforced concrete columns subjected to different single factors is studied and the conclusion is drawn: the impact contact area and impact velocity have the strongest influence on the peak impact force; for the duration of the shock oscillation, it is mainly affected by the impact position, the column height, the longitudinal reinforcement ratio, the axial compression ratio, the impact velocity and the impact mass; when the kinetic energy increment remains basically the same, For the impact response, the impact speed has a greater impact on the impact force peak, but the impact quality has a greater impact on the impact oscillation time. Therefore, the impact response of reinforced concrete columns is mainly affected by the impact energy and the local and overall stiffness of the concrete column.

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