Research on the mechanical properties of reinforced steel fiber concrete column under impact loading

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Abstract. In order to study the effect of different slenderness ratio and axial compression ratio on the lateral impact resistance of reinforced steel fiber reinforced concrete columns, the impact models with different slenderness ratio and continuously varying axial compression ratio were established to analyze the lateral impact resistance of the components. The results show that the proper axial compression ratio is helpful to improve the anti-impact ability of the components. Under normal working conditions, columns with a slenderness ratio of less than 6.5 are recommended to not exceed the axial compression ratio 0.6, for columns with slenderness ratio greater than 12, the axial compression ratio should not be less than 0.3. For columns that may be subjected to impact, the slenderness ratio should not exceed 14.

1. Introduction

Steel fiber reinforced concrete (SFRC) is a kind of composite material which is formed by adding a certain amount of steel fiber randomly distributed in common concrete. Since Portland cement was invented in the 19th century, cement and concrete have been widely used in engineering, transforming public and roads, but in the daily use and experimental research, people have found that concrete has many shortcomings, such as brittle nature, low tensile strength, poor durability, crack resistance. In order to improve the inherent defects of concrete, reinforced concrete structures are formed by combining steel bars and concrete, which have similar coefficient of linear expansion, to a certain extent, the danger of the sudden failure of the concrete structure due to the low tensile strength is reduced, but the steel is easy to oxidize and rust, which shortens the service life of the reinforced concrete structure and affects the normal use of the structure, how to improve the material weakness of concrete materials has become a new research hotspot. Adding fiber into concrete is a new concrete strengthening technology, and steel fiber concrete is a kind of modified concrete with low cost and good performance.

Due to the double advantages of strength and cost of steel fiber, SFRC is used in military, building and bridge engineering, which may bear dynamic load such as earthquake, even impact and impact during its service period, in order to prevent the progressive collapse of SFRC structures caused by impact, it is very important to study the mechanical properties of SFRC components under impact. The existing experimental study [1] shows that the SFRC material shows the characteristics of ‘micro-cracking but not scattered, cracking but continuous’ when it is impacted. In addition, compared with ordinary concrete, it is precisely because of the ‘inextricable’ connections in SFRC that the impact energy consumption area is larger [2], which improves the impact resistance of the components.

In this paper, the finite element software ABAQUS is used to establish numerical the simulation of reinforced SFRC columns under lateral impact, considering strain rate effect of materials under impact.
The influence of slenderness ratio and axial compression ratio on impact performance was analyzed.

2. Finite element model

2.1. Element type and material characteristics

In this paper, the impact numerical model is divided into three parts: Impact Hammer, steel bar and steel fiber concrete. In the model, steel fiber concrete is modeled as a homogeneous material, the element type is an eight-node reduced linear hexahedron (C3D8R), the deformation is controlled by an hourglass, and the reinforcement is a two-node linear three-dimensional truss element (T3D2), which is defined as a rigid body without considering the deformation of the impact hammer, the element type is discrete rigid body element (R3D4). In the aspect of material, HRB400 is adopted for steel bars, the yield strength is 400MPa and the constitutive relation of steel bar is considered as ideal elastoplastic. The embedded element model is chosen to embed the steel bar into the steel fiber concrete for the simulation calculation, the plastic damage model (CDP) is provided by Abaqus, which can simulate the mechanical behavior of concrete well. In this paper, CDP model is used to analyze the nonlinear behavior of SFRC, the dimensionless form of a quadratic parabola combined with a rational fraction [3]:

\[
y = \begin{cases} 
2x - x^2 & 0 < x \leq 1 \\
0.503(x - 1)^2 + x & x \geq 1 
\end{cases}
\]

the tensile stress-strain curve refers to the following formula [4]:

\[
y = \begin{cases} 
\alpha_1 x + (1.5 - 1.25\alpha_1)x^2 + (0.25\alpha_1 - 0.5)x^4 & 0 < x \\
\alpha_c(x - 1)^{1.7} + x & x \geq 1 
\end{cases}
\]

in which \(\alpha_1\) and \(\alpha_c\) are influence coefficient related to SFRC. Different from the stress under static force, the steel and concrete materials will show obvious strain rate effect under impact, which is shown by the increase of the peak stress and the ultimate stress, steel bars reference Cowper-Symonds model: \(f_{yd} = 1 + (\dot{\varepsilon}/D)^{\frac{1}{3}}\). In this formula, \(f_y\) is the static yield stress of steel bar, \(f_{yd}\) is the dynamic stress when the strain rate is \(\dot{\varepsilon}\), and the parameters are \(n=3.91\), \(D=6844\) s\(^{-1}\). The strain rate effect of concrete adopts the CEB-FIP amplification factor model in European code [5]:

\[
\begin{align*}
\frac{f_d}{\bar{f}_S} &= (\dot{\varepsilon}/\dot{\varepsilon}_s)^{1.026a} & \dot{\varepsilon} \leq 30 \text{ s}^{-1} \\
\frac{f_d}{\bar{f}_S} &= \gamma(\dot{\varepsilon}/\dot{\varepsilon}_s)^{\frac{1}{3}} & \dot{\varepsilon} > 30 \text{ s}^{-1}
\end{align*}
\]

In the formula, \(f_d\) is dynamic compressive strength, \(\bar{f}_S\) is static compressive strength, \(\dot{\varepsilon}_S\) is quasi-static reference compressive strain rate, \(\dot{\varepsilon}_s = -30 \times 10^{-6} \text{s}^{-1}\), \(a = (5 + 9f_s/f_{c0})^{-1}\), the reference value of \(f_{c0}\) is 10MPa, \(lg\gamma = 6a - 2\), and the strain rate effect of concrete in tension is calculated by:

\[
\begin{align*}
\frac{f_{td}}{\bar{f}_{Ts}} &= (\dot{\varepsilon}/\dot{\varepsilon}_s)^{6} & \dot{\varepsilon} \leq 1 \text{ s}^{-1} \\
\frac{f_{td}}{\bar{f}_{Ts}} &= \beta(\dot{\varepsilon}/\dot{\varepsilon}_s)^{\frac{1}{3}} & \dot{\varepsilon} > 1 \text{ s}^{-1}
\end{align*}
\]

In which, \(f_{td}\) is dynamic tensile strength, \(\bar{f}_{Ts}\) is static tensile strength, \(\dot{\varepsilon}_s\) is strain rate value of static test, and \(\dot{\varepsilon}_s = 1 \times 10^{-6} \text{s}^{-1}\), \(\delta = (10 + 6f_s/f_{c0})^{-1}\), \(lg\beta = 7\delta - 7/3\). The lateral impact at medium strain rate is simulated in this paper, so the strain rate is 50s\(^{-1}\).

2.2. Establishment of finite element model

The cross-section of the component is 200mm×200mm, and the longitudinal bars are 4 φ12 steel bars.
The slenderness ratio of the column is controlled by setting different component lengths. The boundary conditions at the bottom of the column are completely fixed, and the top is the loading end. All degrees of freedom except the axial direction are restricted. In order to simulate the real impact and reduce the error as much as possible, a spring element is set to apply axial pressure. One end of the spring is connected to the loading end of the column. By setting the spring stiffness and controlling the displacement of the free end of the spring to achieve a predetermined axial pressure. If the stiffness is set small enough, the axial force change caused by the axial displacement of the column caused by the side impact can be controlled within an acceptable range, so the axial force is almost unchanged during the impact.

The axial force is a static load, Abaqus/Standard module is adopted to solve a wide range of static problems, Abaqus/explicit module is selected for impact process, which adopts explicit dynamic finite element formulation and is suitable for transient dynamic events such as impact. In this paper, the axial force impact coupling action steps are as follows: 1. Establish static analysis model, adopt static constitutive relation for materials, and set restart request in output to prepare for impact analysis; Add a predetermined displacement, i.e., spring compression $x_1$, to the boundary condition of the free end of the spring, submit the analysis and calculate the axial compression $x_2$ caused by the axial force. 2. Copy the model, replace the analysis step with dynamic explicit analysis, adopt the dynamic constitutive model considering strain rate effect, take the calculation result of column static analysis as the initial state in the predefined field, and add the displacement of the free end of the spring as $x_1 - x_2$ again, that is, the corrected spring compression; The impact hammer is given a mass of 200kg and an initial velocity of 10m/s, so that the coupling of axial force and impact is completed.

In the impact model, the impact hammer and SFRC column are in general contact, the normal direction of contact surface is in hard contact, the tangent direction is in penalty function, and the friction coefficient is 0.6. The finite element analysis model is established as shown in Figure 1.

3. Impact response
The axial bearing capacity set in this paper is based on the formula provided in the specification [6]:

$$N \leq 0.9 \varphi (f_e A + f_p A_p)$$

in the formula, $\varphi$ is the stability coefficient related to the slenderness ratio of the component. Because of the lateral impact on the column, there is obvious stress concentration, mainly in the impact interface. The column will produce deflection deformation along the impact direction after being impacted laterally, and the stress will transfer obliquely from the impact part to the bottom support part, which will increase the compressive stress of the concrete at the support part, ‘Lateral bracing’ is applied to the impacted column to prevent it from collapsing. The stress and plastic strain Nephogram of the member are shown in Figure 2 and Figure 3. Although the bottom of the column has an outward displacement due to the impact, it does not crack and invalidate the concrete, because the axial pressure exists and the column is always in the state of compressive stress, it can be seen that the existence of axial compression ratio has a protective effect on the impact of the external concrete.
4. Analysis of impact performance parameters of reinforced steel fiber concrete columns

In the initial model, the slenderness ratio and axial compression ratio of columns were changed to investigate the influence of the above two parameters on the lateral impact resistance of SFRC columns.

4.1. Influence of slenderness ratio and axial compression ratio on lateral displacement

In the same impact model with slenderness ratio, the axial compression ratios are 0, 0.15, 0.30, 0.45, 0.60, 0.75 and 0.90, respectively. The slenderness ratio and axial compression ratio are the main factors that affect the ability of column members to resist lateral impact. In Figure 4, the time-history curves of the lateral displacement of the mid-span column under different axial pressure ratios show that the lateral displacement of the mid-span column increases sharply after being impacted, and eventually stabilizes, with a smaller vibration amplitude. When the axial compression ratio increases, the time to stabilize the displacement gradually decreases, and finally stabilizes at about 0.0045s. The mid-span displacement decreases as the axial compression ratio increases, and finally stabilizes at about 22mm.

Figure 4. Time history curve of mid-span displacement of the component under different axial compression ratio

Figure 5. Variation of maximum lateral displacement in mid span

Figure 5 shows the variation of the maximum lateral displacement in the span at the end of impact under each axial compression ratio with different slenderness ratios. When the axial compression ratio is 0, the lateral displacement increases with the increase of slenderness ratio, because the column with large slenderness ratio has a larger span and stronger deformability, and the lateral bearing reaction force caused by impact has a larger bending moment in the span, so the bearing capacity is lower and the impact resistance is also weak. When the axial compression ratio of the column with large slenderness ratio is 0 or the column with low level and small slenderness ratio is in the state of high horizontal axial compression ratio, the lateral displacement does not tend to be constant and converge, so the displacement value is at a high level and continues to develop at the end of impact, and the shape of the column changes from stable curve balance to unstable continuous lateral movement, that is, the phenomenon of ‘instability’ appears, because the axial pressure does not provide enough ‘lateral support’ when the long column is impacted. However, due to the great axial pressure on the column, the end face of the support is in the oblique transmission path of the impact force, which intensifies the lateral displacement and makes the lateral displacement increase or even not converge. When the slenderness ratio is 18, the column will be defeated by the impact force under all axial compression
ratios.

4.2. Effect of slenderness ratio and axial compression ratio on impact force

Figure 6. time history curve of impact force under different axial compression ratio

Figure 7. variation of peak impact force under different axial compression ratios

Figure 6 is the impact force time history curve of a column with slenderness ratio of 8.5 under different axial compression ratios. At the moment of impact action, the impact force increases sharply and reaches its peak, while the concrete undergoes plastic deformation and lateral displacement increases. After the impact force begins to decay, it reaches a platform value. After a period of time, the impact hammer bounces off, the contact surfaces of the two are separated, and the impact force decays to zero. The column will continue to move sideways under inertia and then remain stationary. By comparison, it is found that the platform value of impact force increases with the increase of axial compression ratio, and the duration of impact action is obviously shortened with the increase of axial compression ratio. The reason is that the column with larger axial compression ratio has better integrity, smaller lateral displacement and faster rebound of impact hammer, so the action time is shorter. At this time, the main way for the column to absorb the impact energy is the plastic deformation of concrete, and the impact platform value of this way is greater.

Figure 7 shows the variation of the peak values of the impact forces on columns with different slenderness ratios with the axial compression ratio. The results show that the peak values of the impact forces increase with the axial compression ratio before the axial compression ratio is 0.3, when the axial compression ratio rises to 0.3, the peak value of the impact force is kept at a certain level, which shows that the axial compression ratio is helpful to enhance the lateral impact capacity of the column, but it also has a suitable range. The stable level of the peak value of impact force is between 1800 and 2300 kN under the simulated impact condition.

5. Conclusions

This paper uses Abaqus to establish a finite element model of SFRC columns under lateral impact, and analyzes and studies the impact performance of SFRC columns with different slenderness ratios under lateral impact. The conclusions are as follows:

1. The peak value of the impact force increases with the increase of the axial compression ratio. When the axial compression ratio is greater than 0.3, the peak value of the impact force remains at a certain level. The longer the axial compression ratio is, the shorter the impact duration.

2. The lateral displacement of components decreases with the increase of axial compression ratio, and the column with small slenderness ratio will lose its stability when the column is subjected to large axial pressure and the long column with large slenderness ratio is subjected to low axial compression ratio, the columns with slenderness ratio of 7 ~ 10 are the most stable in resisting lateral impact. It is suggested that the axial compression ratio of columns with slenderness ratio less than 6.5 should not exceed 0.6, and that of long columns with slenderness ratio greater than 12 should not be less than 0.3. In order to avoid instability, the slenderness ratio of columns that may bear impact should not exceed 14.
Acknowledgments
Funding: This work was part of a key project financially supported by Chongqing Education Commission Science and Technology Research Project (KJ1600502).

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