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Dynamic Behavior of RC Columns Confined with Micro-Expansive Concrete-Filled Steel Tubes Subjected to Lateral Low-Velocity Impact: Experimental and Numerical Study

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Abstract: In order to improve the anti-collision capacity of existing reinforced concrete (RC) columns under vehicle impact load, an experimental study on the anti-collision performance of RC columns strengthened with micro-expansive concrete filled steel tube was carried out. By combining an experiment and finite element calculation, the influence of steel tube strength, micro-expansive concrete strength and steel tube wall thickness on the anti-collision performance of strengthened RC columns were studied. The results showed that the peak displacement of an SM-RC column is 25.9% lower than that of an RC column, due to the increased stiffness, the peak impact force increased by 138.2%. The micro-expansive concrete filled steel tube reinforcement method can significantly improve the anti-collision performance of RC columns and reduce the lateral deformation. Increasing the strength grade of steel tube and thickness of steel tube can greatly improve the impact resistance of strengthened RC columns and reduce the lateral deflection deformation of short columns, compared with steel tube strength Q235, the displacement of Q690 is reduced 47.4%. the displacement of the 8-mm thick steel tube is reduced by 48.1% compared with the 4-mm one. while the strength grade of micro-expansive concrete has little effect on the impact resistance and lateral deflection deformation of strengthened RC columns.

Keywords: RC column; anti-collision performance; impact; steel tube; micro-expansive concrete

1. Introduction

Reinforced concrete (RC) structure is widely used in military and civil fields due to its excellent structural properties. However, serious damage often occurs on RC structures under impact loads. Nowadays, with the rapid development of the economy, the traffic volume is increasing, and the load borne by the pier is increasing accordingly. In addition, vehicle collision accidents occur frequently. Once the column fails, it will cause the collapse of the super-structure and lead to engineering accidents. Considering the risk of terrorist attacks, the requirements for the bearing capacity of the column during service become higher. Due to performance degradation, the original column is often difficult to bear the load under vehicle impact. Therefore, it is urgent to study the reinforcing technique of the existing RC columns and their anti-collision performance [1–3].

At present, many researchers have carried out a large number of experimental and theoretical studies on the mechanical performance of RC columns under lateral impact load [4–9]. For example, Zhou [10] found that the stirrup ratio and axial compression ratio have little effect on the peak impact force of the structure by using the experiment and finite element method, but the hoop ratio has a great influence on the failure mode.
The smaller the hoop ratio is, the easier shear failure is to occur, otherwise, the bending shear failure is easy to occur. Besides Fan [11] et al. found that the stirrup ratio affects not only the overall failure, but also the local failure. In addition, through experiments and finite element research, H. Hao et al. [12] found that the contact area between the hammer head and specimen will affect the magnitude of impact force peak value, and using the area surrounded by the impact force-displacement curve and the coordinate axis to reflect the energy absorption capacity of RC column after impact will produce large errors. Furthermore, Chen et al. [13] analyzed the distribution of impact force at each position of RC column after impact theoretically and put forward corresponding empirical formulas to predict the distribution of impact force along the column height. Moreover, Fu et al. [14] conducted drop hammer impact tests on 21 RC columns and studied the evolution and development process of cracks by using DIC technology and high-speed camera. It was found that under the action of low-speed impact load, concrete cracks begin from the bottom and expand to the loading point, showing mainly bending failure mode. While under high-speed impact load, concrete cracks first appear near the loading point and expand downward to the bottom, showing a shear failure mode.

RC columns will inevitably be impacted and damaged by vehicles during service, which will lead to a sharp decline in bearing capacity. In order to avoid disastrous consequences after impact, many researchers have studied the anti-collision ability of strengthened RC columns [15,16]. For instance, Liu et al. [17] conducted an experimental study on the impact resistance of RC columns strengthened with CFRP and considered that when the RC column is wrapped with a layer of CFRP, it can significantly reduce the damage of concrete and the displacement of structure, and the failure mode changes from brittle failure to ductile failure. Besides, Wei et al. [18] found through the drop weight impact test of UHPC strengthened RC beam that there are obvious diagonal shear cracks near the loading point, and the greater the impact energy, the more prone to shear failure. UHPC can absorb part of the impact energy, effectively prevent crack propagation, and significantly improve the impact resistance of the beam. In addition, Kadhim et al. [19] developed a three-dimensional finite element model of RC beam strengthened with CFRP under impact load and verified that the finite element model has high calculation accuracy by using the experiment data of Pham and Hao et al. [20], it found that strengthening with CFRP material can significantly reduce the deflection and deformation of RC beam under impact load. Moreover, Lu’s team [21] verified that the anti-collision performance of steel tube strengthened RC column is obviously better than that of RC column through the impact test. Huang et al. [22] carried out axial compression experiments on micro-expansive CFST columns. The paper indicates that in the elastic stage, The bearing capacity of micro-expansive CFST is 5~20% higher than that of ordinary CFST. Lu et al. [23] conducted axial compression experiments on six steel fiber-reinforced micro-expansive self-compacting concrete short columns. The experimental results indicate that using micro-expansive technology can significantly improve the bearing capacity of steel fiber-reinforced concrete short columns. Xu et al. [24] conducted experiment investigation on the axial compression performance of short columns of steel pipe micro-expansion high strength concrete, which shows that after the concrete is mixed with an expansion agent to produce self-stress, the brittleness of high strength concrete is significantly improved, and the self-stress productid by micro-expansion has an optimal value.

To sum up, most studies are focused on the axial compression performance and seismic performance of RC columns, and relatively few studies are performed on the impact resistance, especially the impact resistance of strengthened RC columns. Considering that micro-expansive concrete can effectively solve the engineering problems such as not densely filling and void in the middle caused by concrete shrinkage. In this paper, the strengthening method of ordinary RC columns reinforced with micro-expansive concrete-filled steel tube (SM-RC) is proposed, and the experimental study on the collision resistance of one RC column reinforced with micro-expansive concrete-filled steel tube and one control RC column is carried out. The influence of key factors such as steel tube strength,
steel tube wall thickness and micro-expansive concrete strength on its collision resistance are analyzed, which can provide a reference for the design of anti-collision capacity of RC column.

2. Experimental Design

2.1. Specimen Design

In order to study the failure mode and mechanical performance of the SM-RC column and verify the accuracy of finite element calculation results, the anti-collision performance tests of one SM-RC column and one control RC column are carried out. The RC column with a section size of 250 mm × 250 mm, the section size of the SM-RC column is 278 mm × 278 mm, and the column height is 1050 mm. The longitudinally stressed steel bars adopt 8 grade HRB400 spiral rib steel bars with a diameter of 14 mm, and the stirrups adopt grade HPB300 smooth steel bars with a diameter of 8 mm. In order to ensure that no slip occurs in the specimen during the impact experiment, a reinforced concrete base with a size of 1000 mm × 650 mm × 500 mm is arranged at the bottom of the SM-RC column. The specific dimensions are shown in Figure 1.

The thickness of the reinforced layer of steel tube micro-expansive concrete is 14 mm, the wall thickness of steel tube is 4 mm and the thickness of micro-expansive concrete is 10 mm, as shown in Figure 1. During the construction process, first remove the laitance on the concrete surface, put the fabricated steel tube into the RC column, then fix the steel plate on the base of the RC column with expansion bolts, and then pour micro expansion concrete into the gap between the steel tube and RC column. In order to prevent debonding damage between the steel tube and platform during the impact experiment, a layer of 50 mm thick ultra-high-performance concrete is poured at the bottom of the steel tube for local reinforcement during construction.

2.2. Material Properties

As shown in Table 1 of detailed specimen parameters, the strength grade of concrete is C20, which is made of ordinary Portland cement, fine river sand, crushed stone (the maximum particle size of aggregate is less than 20 mm) and water according to a certain mix proportion. During the pouring process of concrete, three cube samples of 150 mm × 150 mm × 150 mm are randomly set aside to determine the compressive strength. After curing for 28 days under standard conditions, its average compressive strength is 20 MPa.
Table 1. Detailed parameters of test specimens.

| ID   | Dimensions mm × mm × mm | Concrete Strength of Materials/MPa | Longitudinal Rebar | Stirrups | Tube | Micro-Expansive Concrete |
|------|-------------------------|------------------------------------|--------------------|----------|------|-------------------------|
| RC   | 250 × 250 × 1050        | 20                                 | 400                | 300      | 235  | none                    |
| SM-RC| 278 × 278 × 1050        | 20                                 | 400                | 300      | 235  | none                    |

The strength grade of micro-expansive concrete is C80, which is made of ordinary Portland cement, fly ash, silica fume, mineral powder, fine river sand, crushed stone (the maximum particle size of aggregate is less than 20 mm), shrinkage inhibition materials, water reducer and water according to a certain mix proportion. Similarly, during pouring, three cubic samples of 150 mm × 150 mm × 150 mm were randomly reserved to measure their compressive strength, and the average value of their compressive strength was 80 MPa after 28 days of curing.

The longitudinal reinforcement adopts HRB335 hot-rolled ribbed reinforcement with a diameter of 14 mm, the stirrup adopts HRB300 plain round reinforcement with a diameter of 8 mm, and the steel tube adopts Q235 high-strength seamless steel tube. According to the standard of Tensile test of metallic materials Part 1: room temperature test method (GB/T 228.1-2010), the tensile yield strength of HRB335 and HRB300 steel bars are 335 MPa and 300 MPa respectively, the tensile yield strength of Q235 steel tube is 235 MPa and its elastic modulus is 210 GPa.

2.3. Loading Device and Layout of Measuring Points

The test was completed in the impact laboratory of Nanjing University of Technology. The whole test system consists of traction truck, guide rail, reaction device, drop weight loading system and traction device, as shown in Figure 2. One end of the traction rope is connected with the traction truck, and the other end is connected with the hammer head of mass $M$. The horizontal impact speed of the traction truck is controlled by adjusting the hammer head mass $M$ and the lifting height. It should be noted that when the traction truck is close to the impact position, the traction rope will fall off automatically, and the traction truck will impact the specimen in a free sliding way. It should be noted that the impact speed of the truck is the ratio of the distance from the speed sensor to the collision surface of the specimen and the time from the truck triggering the sensor to contact the specimen. The base of the specimen is fixed in the ground anchor system of the loading platform through two front and rear high-strength screws, as shown in Figure 2.

Figure 2. Schematic of experimental device.
Figure 3 shows the process details of the specimen, and Figure 3c shows the drilling of the expanded steel plate and fixing of the expanded steel plate on the platform through expansion nails.

During the test, the impact force is measured by the pressure sensor on the back of hammer head. The punch position of the truck contacts the area between the displacement gauges B and D. At the same time, a displacement sensor is separately set at the height of 240 mm, 340 mm, 440 mm and 1000 mm from the column bottom to measure the deflection of the specimen along the height direction, as shown in Figure 4. The displacement sensor adopts the KTC LWH ranging displacement sensor with a range of 200 mm (Figure 5a), it is embedded into the back of the pre-drilled specimen through the screw. The dynamic response process of the specimen is photographed by SA-Z 200K high-speed camera (Figure 5b) in Japan, and the acquisition frame rate is 2000 fps. The sampling rate of load cell, displacement and velocity sensor is 100 kHz. In the whole experiment, the free fall of the drop hammer drives the truck to move forward, so as to impact the test piece.

Figure 4. Layout of measuring points of the displacement meter.
3. Experimental Results

3.1. Failure Mode

For the control RC columns, the failure mode of the specimen is mainly shear failure. As shown in Figure 6, the crack extends obliquely downward from the bottom of the impact position to the bottom of the column, and finally, oblique shear failure occurs. The included angle between the concrete oblique crack and horizontal direction is about 45°. The micro-expansive concrete filled steel tube strengthened RC column is mainly flexural failure, which is mainly manifested in the partial void between the bottom of the UHPC layer and the bearing platform, and cracks appear in the UHPC at the bottom of the collision surface. As shown in Figure 6, there is no local buckling on the steel tube surface of the test column body. The test results show that the shear capacity of RC columns reinforced with micro-expansive concrete filled steel tubes can be significantly improved.

The speed at which the truck impacts the RC column is about 3.69 m/s, and that impacts the strengthened RC column is about 4.09 m/s. The dynamic response of the specimen during the impact is shown in Figure 7. For the RC columns, the impact force reaches its peak value of 415.4 kN at about 8 ms. At this time, the maximum lateral deflection deformation at the top of the specimen is 34 mm, and two obvious concrete cracks are generated along the 45° direction from the contact area between the impact head and the column body to both ends, as shown in Figure 7b. As shown by the medium red dotted line, it shows obvious shear failure characteristics. For the RC column strengthened
by steel tube micro-expansive concrete, the impact force reaches its peak value of 989.7 kN in about 1.5 ms. At this time, the maximum lateral deflection deformation at the top of the specimen is only 2.062 mm, and there is no obvious change in the column body. The above analysis shows that the RC column has large stiffness and stability after being strengthened by the steel tube micro-expansive concrete with good deformation resistance.

Figure 7. Impact process of experiment specimen. (a) Initial moment. (b) Peak force moment. (c) Peak displacement moment. (d) Final state.

The destroyed shape when the lateral deflection of all test specimens reaches their peak value is shown in Figure 7c. As shown in Figure 7c, the RC column reaches its peak value of lateral deflection of 105.7 mm at 44 ms, and the concrete inclined crack under the contact area between the hammer head and the column body continues to expand, forming an obvious shear failure crack. While the SM-RC column reaches its peak value of lateral deflection of 78.3 mm at 21 ms, which is about 74.1% of the RC column. Although the SM-RC column has a significant lateral position at this time, the steel tube does not reach its yield strength and still can bear the load. The reason why the impact force action time of SM-RC specimen is shortened is that under the protection of steel tube micro-expansive concrete reinforcement layer, the internal concrete has no shear failure during the impact process, thus the stiffness degradation of the test specimen is not significant. When the RC column is subjected to impact load, the specimen has apparent oblique shear failure, resulting in rapid reduction of stiffness and obvious prolongation of action time.

The failure patterns of all test specimens at the end of dynamic response are given in Figure 7d. Although the impact speed of the SM-RC column truck is greater than that...
of the RC column, which is about 1.1 times that of the RC column, the SM-RC column does not have significant shear failure characteristics, the steel tube does not reach its yield load, and the lateral peak deflection is about 74.1% of that of the control RC column. The experiments results show that the micro-expansive concrete filled steel tube to enhance the RC column can significantly improve the stiffness of the RC column, impact resistance and reduce its lateral deflection.

3.2. Impact–Time History Curve

The impact force-time history curves of all test specimens are shown in Figure 8. According to the dynamic response process, it can be divided into three different stages: the first stage is the rising stage. After the truck is impacted by a large acceleration, the impact force increases linearly. At this stage, after the truck hammer head contacts the specimen, the RC column reaches the peak value in about 0.8 ms and the SM-RC column reaches the peak value in about 1.5 ms, this is because the stiffness of the two specimens is different, thus the time to reach the peak value is also different. The peak value of the SM-RC column with large stiffness reaches 989.7 kN, while the peak value of impact force for the RC column is 415.4 kN. In the first stage, it is caused by the large acceleration of the truck transmitted to the specimen and the small displacement of the specimen. In the second stage, after the specimen contacts the hammer head, the truck speed decreases so the impact force decreases gradually. The third stage is the descending stage, when the impact energy is dissipated, and the impact force begins to gradually decrease to zero, and the impact force curve shows a downward trend. When the impact force becomes zero, it indicates that the truck is separated from the specimen. Through the above analysis, the peak impact force of the SM-RC column is 138.2% higher than that of the RC column, indicating that the stiffness and anti-collision ability of the RC column are significantly increased after being strengthened by steel tube micro-expansive concrete. The negative impact force in Figure 8 may be caused by other noises in the experiment.

![Impact-time history curve.](image)

**Figure 8.** Impact-time history curve.

3.3. Displacement–Time History Curve

From the displacement-time history curve in Figure 9, it can be seen that the curves of the RC column and SM-RC column show a similar change tendency. The displacement of the two specimens increases rapidly after being subjected to impact load, and the curve slope decreases gradually. When the truck speed decreases to 0 m/s, the member reaches its peak value of lateral deflection, and then it begins to rebound, and due to plastic deformation, it cannot be recovered completely. Therefore, the test specimen vibrates...
freely after being separated from the truck hammer head. At the moment of hammer head impact, the lateral deflection of the specimen increases rapidly, and then the lateral displacement rebounds significantly. This is because under the action of lateral impact load, the specimen first produces elastic deformation, and then elastic-plastic deformation. After the lateral impact force disappears, the elastic deformation recovers. When the hammer head is separated from the RC column, the column is in a free vibration state until the deformation of the column becomes stable. The peak displacement of the RC column is 105.7 mm and that of the SM-RC column is 78.3 mm. Compared with the RC specimen, although the impact velocity of the SM-RC column is about 110.8% of the RC column, the lateral deflection of the SM-RC specimen is significantly reduced, and its maximum peak displacement is 25.9% lower than that of the RC column, indicating that the composite reinforcement method of steel tube micro-expansive concrete can greatly reduce the lateral deflection of the RC column.

Figure 9. Displacement-time history curve. (a) RC column. (b) SM-RC column.

4. Numerical Calculation

Considering the defects of high material consumption, time and labor cost in impact test, this section gives full play to the advantages of finite element analysis software LS-DYNA. On the basis of experimental research, a refined numerical analysis model of steel tube micro-expansive concrete reinforced RC column is established, and the influence of wall thickness, tensile strength and micro-expansive concrete compression strength on the specimen under impact load is studied. Besides, the failure mode and damage mechanism of the SM-RC column under vehicle impact load are clarified, which provides a reference basis for the engineering application of micro-expansive concrete filled steel tube to enhance the anti-collision performance of RC structure.

4.1. Establishment of Finite Element Model

In the finite element model, the longitudinal reinforcement, stirrup and steel tube are modeled by beam element, and in the truck model, ordinary concrete and UHPC are modeled by the solid element, as shown in Figure 10. As the mesh size has a large influence on the finite element results of the structure under impact load, sensitivity analysis is carried out by changing the mesh size of different materials. It is found that when the mesh density is less than 10 mm, the impact force, failure mode and lateral displacement of the finite element results remain basically unchanged. Considering computational efficiency, the grid size used in this paper is set at 10 mm.
4.2. Constitutive Model of Materials

CSCM (The Continuous Surface Cap Model) constitutive relationship model considering dynamic damage evolution in LS-DYNA software is widely used for concrete, and the accuracy of the model has been verified in [9,10]. The concrete density is 2380 kg/m$^3$ and the compressive strength is 20 MPa. * MAT_CSCM is also used for UHPC and micro-expansive concrete. According to the definition of CSCM, the density of UHPC is 2600 kg/m$^3$, the elastic modulus is 42 GPa, the density of micro-expansion concrete is 2400 kg/m$^3$, and the elastic modulus is 35 GPa. The strain rate is considered in the material model. The action of micro-expansion in finite element analysis is achieved by applying temperature load on concrete using the keyword * MAT_ADD_THERMAL_EXPANSION. The linear expansion coefficient of micro-expanded concrete is $10 \times 10^{-6}$/°C in the vertical direction and $10 \times 10^{-5}$/°C in the radial direction. The temperature applied to the concrete is 45° [25]. The unit is mm-MPa-N-t. The density of longitudinal reinforcement, stirrup and truck is 7850 kg/m$^3$, the elastic modulus is 206 GPa, and the yield strength is 400 MPa, 300 MPa and 235 MPa respectively. The specific material model is shown in Table 2.

Table 2. Constitutive model and parameters of material.

| Component | Material Model | Density (kg/m$^3$) | Elastic Modulus (GPa) | Poisson’s Ratio | Yield Stress |
|-----------|----------------|--------------------|-----------------------|----------------|--------------|
| rebar     | MAT_PIECEWISE_LINEAR_PLASTICITY | 7850               | 206                   | 0.3            | 400          |
| truck     | MAT_PLASTIC_KINEMATIC          | 7850               | 206                   | 0.3            | 235          |
| stirrup   | MAT_PLASTIC_KINEMATIC          | 7850               | 206                   | 0.3            | 300          |
| tube      | MAT_PLASTIC_KINEMATIC          | 7850               | 206                   | 0.3            | 3400         |

4.3. Contact Relationships and Boundary Constraints

The * CONTACT keyword is used in a numerical calculation in this paper to simulate the interaction between different components, so as to transfer the interaction force between different components under impact load. The key words * CONTACT_AUTOMATIC_SURFACE_TO_SURFACE are used to define the contact between steel tube and micro-expanded concrete, between UHPC and the inner wall of steel tube, between micro-expanded concrete and original RC column, and between truck and whole specimen. The static and dynamic friction coefficients are both set as 0.3. A common joint is used between longitudinal reinforcement, stirrup and ordinary concrete, and the contact mode of partial area “TIE” is adopted between UHPC and surface of the concrete cap, the expanded area of steel pipe and the overlap part of UHPC is * CONTACT_TIED_SURFACE_TO_SURFACE. In order to better reproduce the test results, appropriate boundary conditions are also required in the finite element model. Considering that the bottom of the RC column is fixed on the test table by bolts and ground
anchors, the base is simplified as a fixed constraint, that is, $F_x = F_y = F_z = F_{rx} = F_{ry} = F_{rz} = 0$. The truck is only allowed to move in the horizontal direction, i.e., $F_y = F_z = 0$.

5. Model Validation

In order to verify the rationality of the proposed numerical model, based on the experimental results of the above analysis, the numerical simulation results are compared with the experimental results. From Figures 11–13, the failure mode, impact force-time history curve and displacement-time history curve are compared. It is concluded that the numerical simulation results are in good agreement with the experimental results. Therefore, the established numerical model can reasonably predict the dynamic mechanical behavior of steel tube micro-expansive concrete reinforced RC columns under impact load.

![Figure 11](image1.png)

**Figure 11.** Experiment and finite element failure modes. (a) Displacement peak of test and FE (b) Residual displacement of test and FE.

![Figure 12](image2.png)

**Figure 12.** Comparison - impact-time history curves from test and finite element simulation.
5.1. Failure Mode

In this section, firstly, the effectiveness of the model is preliminarily verified by comparing the test failure modes of steel tube micro-expansive concrete strengthened RC column and the finite element results. As shown in Figure 11, the time when the test results and finite element results reach the peak displacement of about 0.02 s, and there is no obvious local buckling of the column body, plastic strain appears near the impact area in the finite element results. Since the plastic strain of the steel tube is small and there is no local buckling, it cannot be directly observed in the experimental results. In order to further verify the accuracy of the finite element model, the impact force-time history curve and displacement-time history curve are compared and analyzed below.

5.2. Impact-Time History Curve

It can be seen from the impact force-time history curves of the test columns in Figure 12 that the development of the impact force-time history curve of the two is basically consistent. By comparing the impact force-time history curve in the test and finite element model, the RC column reaches the impact force peak value in about 0.8 ms, while the SM-RC column reaches the impact force peak value in about 1.5 ms, which is consistent with that of the experimental results. After the RC column is subjected to the impact load, the truck accelerates the specimen and moves forward together, thus the truck and the specimen accelerate together, after being impacted, the oblique shear failure of the RC column leads to the rapid reduction of stiffness, and less force can force the specimen to move. Therefore, the time to reach the peak displacement of the RC column will be longer than that of the reinforced column. It can be seen that the tested peak impact force of the test is 989.7 kN, while the simulated value is 1090.2 kN, and the maximum error is only 10.1%, which indicates that the finite element model can better simulate the mechanical properties of structural columns under impact load. The certain error in the peak value of impact force is due to the fact that there are many uncontrollable factors in the dynamic load test. The results can provide reference significance for practical engineering within a certain error range.

5.3. Displacement-Time History Curve

As shown in Figure 13, the solid line in the figure represents the test result and the dotted line represents the finite element result. Comparing the displacement-time history curves of four measuring points of A, B, C, and D, the test peak value of measuring point A is 78.3 mm, the finite element peak value is 73.7 mm, and the error between them is 5.8%.
The peak value of measuring point B is 39.1 mm, the finite element peak value is 38.3 mm, and the error between them is 2%. The peak value of measuring point C is 33.1 mm, the finite element peak value is 32.3 mm, and the error between them is 2.4%. The peak value of measuring point D is 23.8 mm and the peak value of finite element is 21.8 mm, with an error of 8.4%. Due to the complexity of the dynamic load test, the error between experimental results and finite element results is within a reasonable range, thus it can be considered that the model is reliable. After the impact of the truck and the separation of the specimen, the specimen recovers some residual deformation, the vibration is generated due to the existence of kinetic energy, but with the attenuation of energy, the vibration finally tends to stabilize the residual displacement. There is also a certain vibration in the test, but the amplitude is small and not obvious because the finite element simulation is more ideal than the test conditions. It is consistent with the conclusion of the literature [21].

5.4. Parametric Analysis

In order to study the influence of key parameters on RC columns strengthened by micro-expansion concrete filled steel tube under vehicle impact, the finite element model verified by test results was used to analyze the influence of main parameters. It should be noted that in the finite element model results verified by the test, the UHPC layer will be debonded from the RC column cap after the specimen is subjected to impact load, resulting in the phenomenon of warping of the UHPC layer. As a result, the main failure mode of the strengthened RC specimen is bending failure, which will lead to a large deviation in the analysis of displacement size during parameter analysis. Therefore, in order to weaken the influence of bending failure caused by the debonding of the UHPC layer in parameter analysis, the contact between the UHPC and concrete cap in the finite element model in this section is changed from the original partial area “TIE” to all area * CONTACT_TIED_SURFACE_TO_SURFACE. The displacement of point A at the top was selected to analyze the results.

5.4.1. Steel Tube Strength

The commonly used strengths (Q235, Q345 and Q690) of steel tubes in practical engineering structure for parameter analysis, and the change law of impact force-time history curve and displacement time history curve of specimens with different steel tube strength are shown in Figure 14. It can be seen that with the increase of steel tube strength, the impact force increases and the displacement decreases. The impact forces of steel tube strength Q235, Q345 and Q690 are 1171.6 kN, 1253.3 kN and 1390 kN respectively, and the peak displacements are 29.1 mm, 23.1 mm and 15.3 mm respectively. Compared with steel tube strength Q235, the impact force of the Q345 steel tube increased by 6.9% and the displacement decreased by 20.6%. Compared with steel tube strength of Q345, the impact force of the Q690 steel tube is increased by 10.9% and the displacement is reduced by 33.7%. As the strength of the steel tube is improved, the bending strength of the specimen is also improved, thus the specimen has better impact resistance. Through comparative analysis, it can be concluded that the steel tube strength has a significant effect on the displacement of the specimen.
5.4.2. Thickness of Steel Tube

In order to study the influence of steel tube wall thickness on the impact resistance of specimen, steel tubes with a wall thickness of 2 mm, 3 mm and 4 mm are selected for analysis. The variation law of impact force and displacement of the specimen under different steel tube wall thicknesses is shown in Figure 15. It can be seen that with the increase of steel tube wall thickness, the impact force increases and the displacement decreases. When the steel tube wall thickness is 4 mm, 6 mm, and 8 mm, the corresponding impact forces are 1171.6 kN, 1287.2 kN, and 1382 kN respectively, and the corresponding peak displacements are 29.1 mm, 20.7 mm, and 15.1 mm, respectively. The impact force of 6 mm thick steel tube is increased by 9.8% and the displacement is reduced by 28.9% compared with the 4-mm-thick steel tube. The impact force of 8-mm-thick steel tube is increased by 7.4% and the displacement is reduced by 27.1% compared with the 6-mm-thick steel tube. It can be concluded that the increase of steel tube wall thickness leads to the increase of impact force, which is due to the increase of interface geometric size and corresponding section bending stiffness. The impact resistance is enhanced, and the displacement is reduced. Therefore, at the same impact speed, with the increase of steel tube wall thickness, the impact force of the specimen will increase, but the overall displacement of the structure will be reduced.

Figure 14. Different steel tube strength. (a) Impact-time history curve. (b) Displacement-time history curve.

Figure 15. Different thicknesses of tube. (a) Impact-time history curve. (b) Displacement-time history curve.
5.4.3. Micro-Expansive Concrete Strengths

In order to study the influence of micro-expansive concrete strengths on the impact resistance of specimens, 40 MPa, 60 MPa, and 80 MPa strengths are selected for analysis. The variation laws of impact force and displacement of specimens under three different micro-expansive concrete strengths are shown in Figure 16. It can be seen from the curve that the impact force-time history curve and displacement time history curve of the two almost coincide. The strength of micro-expansive concrete is 40 MPa, 60 MPa, and 80 MPa, the corresponding impact forces are 1148.8 kN, 1153.3 kN, and 1171.6 kN, respectively. The corresponding peak displacement is 29.5 mm, 29 mm, and 29 mm respectively. These results show that the strength of micro-expansive concrete has little effect on the impact force and horizontal displacement of SM-RC columns under impact load.

![Figure 16](image_url)

Figure 16. Different micro-expansive concrete strengths. (a) Impact-time history curve. (b) Displacement-time history curve.

5.4.4. Expansion Rate

In order to study the impact of concrete expansion rates on the impact resistance of specimen, the expansion rates of 12%, 15%, and 20% are selected for analysis. The variation laws of impact force and displacement of the specimen under three different concrete expansion rates are shown in Figure 17. It can be seen from that the impact force-time history curve and displacement time history curve of the two almost coincide. When the concrete expansion rate is 12%, 15%, and 20%, the corresponding impact forces are 1171.6 kN, 1168.1 kN, and 1172.7 kN, respectively, and the corresponding peak displacements are 29.1 mm, 28.9 mm, and 29.3 mm, respectively. The results show that the expansion rate in this range has no obvious effect on the impact force and displacement of the specimen. The possible reason is that the filling area of micro-expansive concrete is small, thus the influence of expansion rate is also small.
6. Conclusions

In order to improve the anti-collision performance of the RC column, the dynamic performance of the RC column strengthened by steel tube micro-expansive concrete under vehicle impact load is experimentally studied, and the failure mode, impact force-time history curve and displacement time history curve of the SM-RC column under impact load are analyzed. The main conclusions are as follows:

1. The restraint form of micro-expansive concrete filled steel tube strengthened RC column does not appear obvious local buckling under impact load and greatly reduces the maximum deflection and residual deflection of the specimen compared with the control RC column.

2. Under the vehicle impact load, the RC column mainly occurs shear failure, and the speed of the SM-RC column is 1.1 times higher than that of the RC column, but the column body of the SM-RC column does not buckle, and the column body remains intact.

3. A numerical model for predicting micro-expansive concrete-filled steel tube columns under vehicle impact load is proposed, and the experimental results verify the effectiveness of the numerical model, and the results are in good agreement.

4. The finite element results show that the impact force increases and the peak displacement decreases with the increase of steel tube wall thickness and steel tube strength; The strength and expansion rate of micro-expansive concrete have little effect on the specimens. In order to improve the anti-collision performance of the specimen, the strength and wall thickness of the steel tube can be appropriately improved.

5. The peak displacement of the SM-RC column is 25.9% lower than that of the RC column, Due to the increased stiffness, the peak impact force increased by 138.2%.

6. Because the area of micro-expansive concrete in RC columns reinforced by micro-expansive concrete filled steel tubes is relatively small, the effect is not obvious in the whole specimen. Therefore, it is necessary to study the dynamic response of micro-expansive concrete-filled steel tube columns under impact load.

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