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Research Article

Experimental Study and Numerical Analysis on Impact Resistance of Civil Air Defense Engineering Shear Wall

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In order to study the impact resistance of civil air defense engineering shear wall, the impact resistance of civil air defense engineering shear wall was studied by combining finite element numerical simulation with pendulum impact test. The effects of impact height, pendulum mass, and impact times on the impact resistance of civil air defense engineering shear walls were analyzed. It was shown that when the impact height increased from 0.4 m to 2.5 m, the failure mode of civil air defense engineering shear wall tended to be local impact failure, and the horizontal displacement in the middle of the wall span increased. The concrete crushing occurred in the impact area of the back of the civil air defense engineering shear wall. The increase in the impact height is a negative factor for the impact resistance of the civil air defense engineering shear wall. With the increase of pendulum weight, the number of concrete horizontal cracks in the back of the civil air defense engineering shear wall increased, while the number of vertical cracks decreased, but the impact surface was destroyed. Through multiple impact tests on the civil air defense engineering shear wall, the civil air defense engineering shear wall had accumulated damage. The longitudinally loaded steel on the back reached the ultimate strength, and there are large cracks at the bottom and even collapses. The increase of impact times has a great influence on the impact resistance of the civil air defense engineering shear wall. Through the analysis of the factors affecting the impact resistance of civil air defense engineering shear wall, it provides guidance for civil air defense engineering shear wall to resist impact load.

1. Introduction

As a common vertical component in civil air defense engineering, the shear wall will be subjected to various impact loads in the use process. However, the impact response of reinforced concrete structures is complex [1, 2], and the high strain rate can cause materials in the structure to become harder, stronger, and more brittle [3]. As a special building structure, civil air defense engineering must bear these impact loads in structural design. Therefore, it is vital to study the impact resistance of civil air defense engineering structures under impact load.

In recent years, with the national attention to civil air defense engineering construction, the amount of civil air defense engineering construction increases rapidly, and the impact resistance of structure has become the focus of researchers. Yi et al. [4, 5] studied the influence ratio, wall width, and axial member on the out-of-plane impact resistance of the shear wall; studies have shown that, within a certain range, increasing the reinforcement ratio and axial compression ratio can improve the impact resistance of shear walls, and increasing the wall width and setting edge components can significantly improve the impact resistance of shear walls. Sun et al. [6] studied the failure of steel fiber reinforced concrete panels under drop hammer impact; the results show that, under impact load, the steel fiber reinforced concrete panel avoids punching failure and has better ductility and deformation ability than the concrete panel without steel fiber. Kou et al. [7] studied the impact resistance of high ductility concrete slab under drop hammer impact. The test results showed that there was only a small amount of concrete fragments spalling at the bottom of the RC slab. Yan et al. [8] set slot steel connectors in shear walls to study the impact resistance of steel-concrete-steel composite shear walls; the results show that reducing the spacing of slot steel connectors could significantly reduce the deformation of the wall. Yong et al. [9] studied the dynamic response of reinforced concrete walls under the megalithic impact and verified that the displacement-based model could accurately predict the deformation of the wall through the megalithic impact test. Wu studied the dynamic response of reinforced concrete slab-buffer layer composite structure under rockfall impact and analyzed the influence of different impact velocities and buffer layer thickness on the damage of reinforced concrete slab [10]. Hossain et al. [11] conducted an in-plane impact test and finite element analysis on the new composite wall (filled with two layers of the profiled steel plate and one layer of concrete). The results showed that, through repeated impact tests, the finite element model could accurately predict the maximum horizontal displacement and maximum acceleration at the top of the wall.

Wang [12] studied the damage of civil air defense projects under different levels of nuclear explosion shock waves. The results show that shear walls play an important role in resisting impact loads during the transition from peacetime to wartime. Liu et al. [13] through to the civil air defense engineering shallow buried structure near the bomb explosion test research, the overpressure value acting on the civil air defense engineering structure is related to the stiffness of the structure, and the maximum load should be taken in the impact resistance design of the structure. Lee et al. [14] studied the impact resistance of reinforced concrete slab under the impact of the hard projectile, and the test results showed that reducing the rebar spacing improved the local impact resistance of reinforced concrete slab. Huang studied the antiexplosion performance of civil air defense engineering board with a buffer layer; the study shows that adding a buffer layer can play a good role in energy consumption and load reduction [15].

At present, there are many studies on the impact test and numerical simulation of ordinary reinforced concrete columns [16–20], beams [21–26], and walls (plates) [27–33]. Civil air defense engineering shear walls play an important role in civil air defense engineering structures and are also the main force components under impact loads. Therefore, this paper studies the impact resistance of civil air defense engineering shear walls. The shock wave generated by the explosive load is converted into surface load and applied to the impact surface. The numerical simulation and pendulum impact test are combined to study the influence of impact height, pendulum mass, and impact times on the impact resistance of civil air defense engineering shear wall.

2. Material Parameters and Model Validation

2.1. Material Parameter. In the test, ANSYS/LS-DYNA software is used to simulate the dynamic response of civil air defense engineering shear walls to resist impact load. The concrete damage model provided by LS-DYNA mainly includes MAT 72, MAT 96, MAT 111, and MAT 159. In the face of medium- and low-speed impact load, * MAT_CSCM (MAT 159) element can well simulate the plastic damage of concrete [34]. The model takes into account the damage and hardening of materials. Therefore, the MAT 159 concrete model is selected in this study. The maximum aggregate size of concrete is 25 mm, and the strength of concrete is C35; detailed material parameters are listed in Table 1. Considering that the concrete unit will be eroded after being impacted, the ERODE parameter in the CSCM model is set to 1.1, and the size of this parameter can also be adjusted according to the actual situation.

The *MAT_PLASTIC_KINEMATIC (MAT 3) model in LS-DYNA was selected as the load-bearing rebar of civil air defense engineering shear wall, and an elastic-plastic material model related to the strain rate and with failure was proposed. This model can adopt isotropic hardening ($\beta = 1$), kinematic hardening ($\beta = 0$) , or mixed hardening ($0 < \beta < 1$). The strain rate effect was considered by the Cowper-Symonds model, and the viscoplastic strain rate effect ($VP = 1$) was recommended. The relationship between the yield stress of the model and the plastic strain and the strain rate can be expressed as

$$\sigma_Y = \left(\sigma_0 + \beta E_p \varepsilon_p^{\text{eff}}\right)\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{(1/P)}\right], \quad (1)$$

where σ_0 is the initial yield stress, $\dot{\varepsilon}$ is the strain rate, $\varepsilon_p^{\text{eff}}$ is the effective plastic strain, β is the hardening parameter, C and P are the strain rate parameter, and E_p is the plastic hardening modulus determined by

$$E_p = \frac{EE_t}{E - E_t}, \quad (2)$$

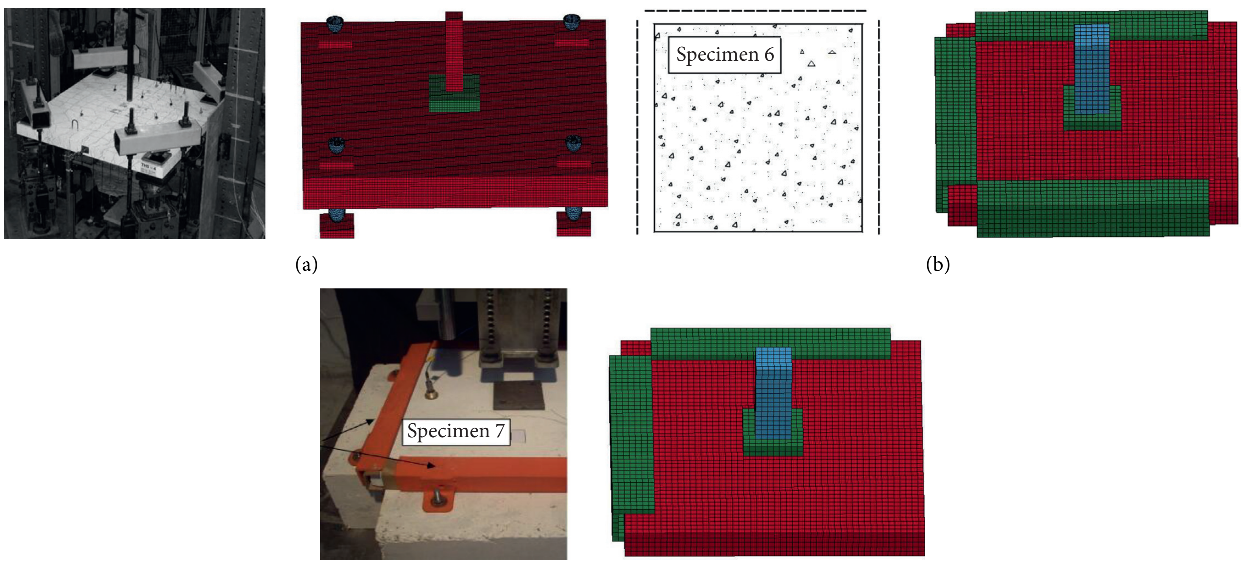
where E is elastic modulus and E_t is the tangent modulus.

2.2. Model Verification. The selected material model is verified accurately in the finite element simulation of reinforced concrete beam drop hammer impact. In order to further verify the material model, the full model modeling method is used to simulate the drop hammer impact of reinforced concrete slabs without fiber in [35] and slabs 6 and 7 in [36]. The finite element model is established according to the boundary conditions in the test device to simulate the impact test more accurately and improve the reliability and accuracy of the finite element simulation. The test boundary conditions and the finite element model are shown in Figure 1.

The displacement time-history curves of TH2 specimen under impact mass of 150 kg and 210 kg in [35] and plate 6 and plate 7 fixed on both sides in [36] were compared with the finite element simulation, as shown in Figure 2. It can be seen from the displacement time-history curve in Figure 2 that the selected material model is accurate in simulating the dynamic response of reinforced concrete slab under the impact, which is further applied to the finite element simulation of reinforced concrete wall pendulum impact.

Table 1: Material parameters.

Components	Material model	Material parameters
Concrete	*MAT_CSCM_CONCRETE	ρ = 2400kg/m^3, f_c = 35 MPa, D = 25 mm
Longitudinal reinforcement and horizontal distribution reinforcement of the shear wall	*MAT_PLASTIC_KINEMATIC	ρ = 7800 kg/m^3, E = 205 GPa, υ = 0.3 f_y = 442 MPa, f_u = 614 MPa
Stretching steel bar	*MAT_PLASTIC_KINEMATIC	ρ = 7800 kg/m^3, E = 205 GPa, υ = 0.3 f_y = 417 MPa, f_u = 573 MPa
Cushion block and pendulum mass block	*MAT_ELASTIC	ρ = 7800 kg/m^3, E = 205 GPa, υ = 0.3



(c)

Figure 1: Comparison between the test device and finite element simulation. (a) Comparison of boundary conditions in reference [35]. (b) Comparison of trilateral clamped boundary conditions in [36]. (c) Comparison of boundary conditions of two clamped edges in [36].

3. Test Contents

3.1. Specimen Design. In this experiment, according to the scale ratio of 1 : 2, six groups of simulation analysis and two groups of experimental research on the impact resistance of civil air defense engineering shear walls were carried out to analyze the influence of pendulum mass, impact height, and impact times on the impact resistance of civil air defense engineering shear walls, as shown in Table 2. The number of civil air defense engineering shear walls is composed of three parts: the first letter Q represents civil air defense engineering shear wall, the second number represents pendulum mass, and the third number represents impact height. For example, Q-1-0.4 is the impact response of civil air defense engineering shear wall under pendulum mass of 1 ton and impact height of 0.4 m. Among them, Q-2-0.25, Q-2-0.5, and Q-2-2.0 are experimental studies, and the remaining numbers are finite element simulation analysis. The detailed size and reinforcement of the specimen are shown in Figure 3. The concrete strength grade in the specimen is C35, and the mix ratio is shown in Table 3.

All the steel bars used in the shear wall specimens of civil air defense engineering are HRB400 hot rolled ribbed bars with diameters of 6 mm, 8 mm, 20 mm, 22 mm, and 25 mm, respectively. Tensile tests were carried out on the above steel bars to obtain the yield strength f_y and ultimate strength f_u, as shown in Table 4.

3.2. Test Device. The impact test adopts the pendulum impact device independently developed by our research group. As shown in Figure 4, the total weight of the pendulum is composed of 10 counterweight blocks, and each counterweight block weighs 500 kg. The weight of the pendulum can be adjusted by increasing or decreasing the number of counterweights, and up to 10 counterweights can be increased. A thick steel plate of 340 mm × 340 mm × 50 mm was pasted at the center of the civil air defense engineering shear wall, and the impact load was converted into surface load and applied on the impact surface. The pendulum hammer was contacted with the civil air defense engineering shear wall through a cylindrical impact force sensor with a diameter of 300 mm. A hydraulic jack was set at the top of the upper beam, and the hydraulic jack could impose a maximum pressure of 2000 kN.

3.3. Measurement Scheme. The data needed for finite element simulation and impact test are as follows:(1) time-history curve of impact force, (2) time-history curve of mid-span horizontal

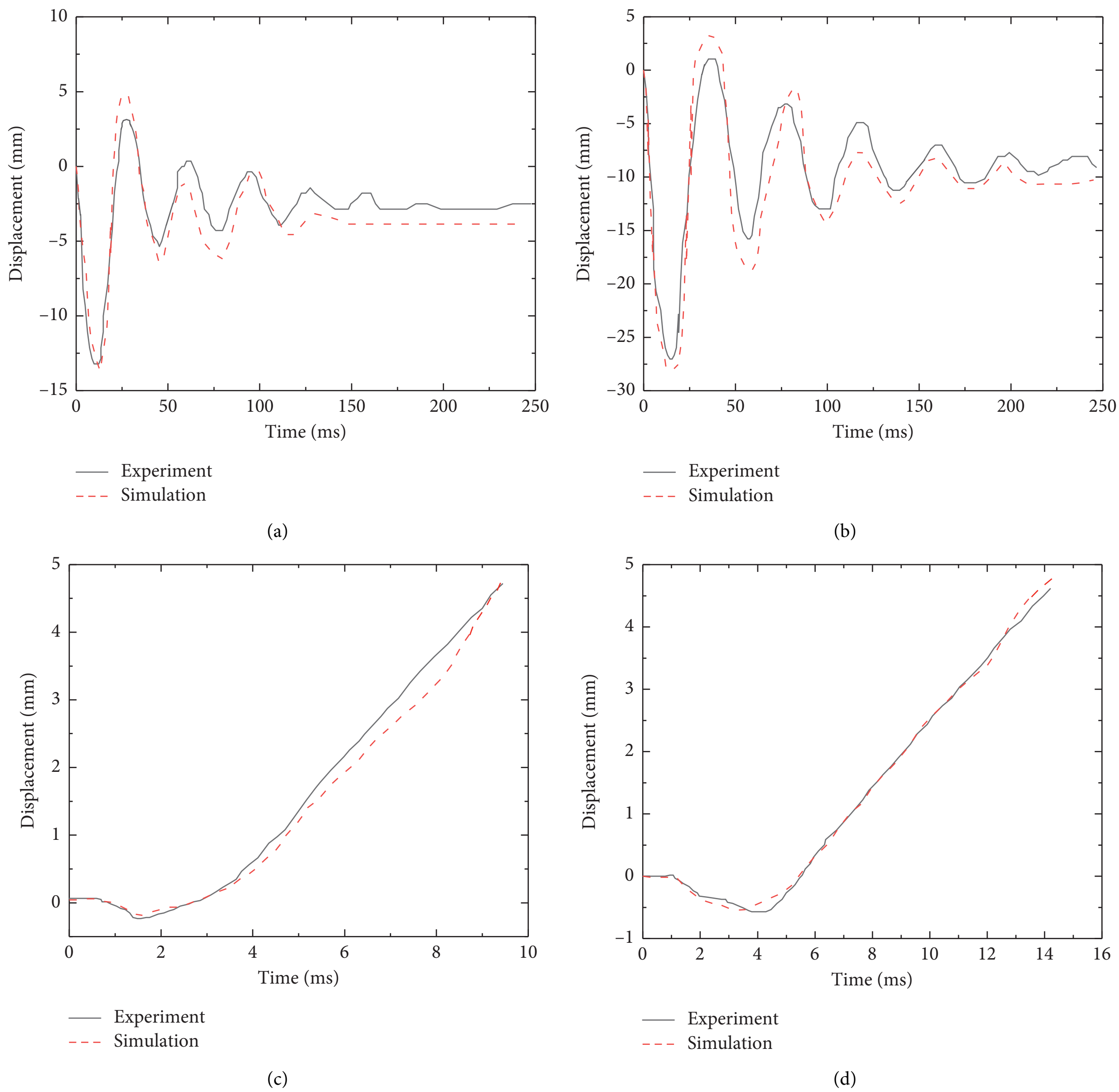


Figure 2: Comparison of displacement time-history curve test and simulation of the reinforced concrete slab. (a) TH2-1. (b) TH2-3. (c) Reinforced concrete slab 6. (d) Reinforced concrete slab 7.

Table 2: Pendulum mass and impact height.

Pendulum mass (ton)	Impact height (m)	Shear wall number of civil air defense engineering
1	0.4	Q-1-0.4
	1.3	Q-1-1.3
	2.5	Q-1-2.5
2	0.25	Q-2-0.25
	0.4	Q-2-0.4
	0.5	Q-2-0.5
	1.3	Q-2-1.3
	2.0	Q-2-2.0
	2.5	Q-2-2.5

displacement of the wall, (3) rebar strain, (4) impact energy, (5) residual displacement in the mid-span of the wall, and (6) crack width. The location of the rebar strain of the measuring point is shown in Figure 5. Because the civil air defense engineering shear wall adopts double reinforcement, F-X represents the measuring point of the rebar strain of the impact surface of the

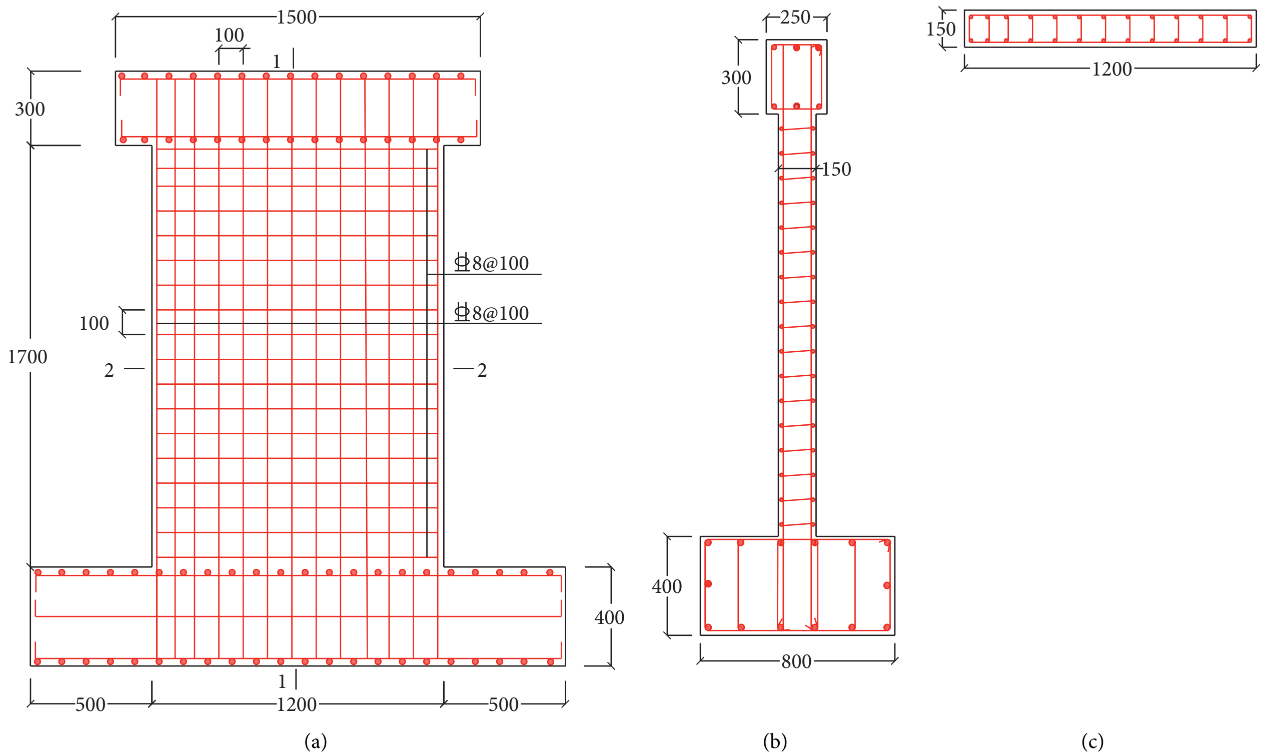


FIGURE 3: Shear wall size and reinforcement diagram of civil air defense engineering. (a) Shear wall profile. (b) 1–1 Profile. (c) 2–2 Profile.

TABLE 3: Concrete mix proportions for C35.

Strength grade	Water (kg·m^{-3})	Cement (kg·m^{-3})	Sand (kg·m^{-3})	Stone (kg·m^{-3})	Flyash (kg·m^{-3})
C35	170	345	765	980	55

TABLE 4: Yield strength and ultimate strength of steel bars.

Bar diameter (mm)	f_y (MPa)	f_u (MPa)
6	417	573
8	442	614
20	470	621
22	469	635
25	483	632

Notes: f_y = yield strength; f_u = ultimate strength.

civil air defense engineering shear wall, and B-X represents the measuring point of the rebar strain of the back of the civil air defense engineering shear wall.

4. Impact Test Result Analysis

4.1. Failure Mode of Civil Air Defense Engineering Shear Wall. Figure 6 compares the failure mode of the impact test and simulation results of the civil air defense engineering shear wall when the impact height is 0.4 m and the pendulum mass is 2 tons; in order to observe the development of cracks on the back and side of the wall, the red thin line is used to describe the crack position. The length of the red thin line represents the crack length. The red in the finite element simulation indicates the crack width and damage degree of the wall. The deeper the color, the greater the damage degree. From Figures 6(a) and 6(d), it can be seen that there is almost no crack in the impact surface of the civil air defense engineering shear wall, but there is a long crack at the root of the impact surface, which is consistent with the simulation results. Considering that the civil air defense engineering shear wall is subjected to the impact load and the root constraint is a fixed constraint, in the instant of the impact, in order to prevent the displacement of the civil air defense engineering shear wall, the root is subjected to a large bending moment and the root cracking occurs. It can be seen from Figure 6(b) that with the impact area on the back of the civil air defense engineering shear wall as the center, the cracks spread radioactively around, and the number of horizontal cracks is more than vertical cracks. This is because the civil air defense engineering shear wall is subjected to impact load, and the concrete absorbs part of the impact

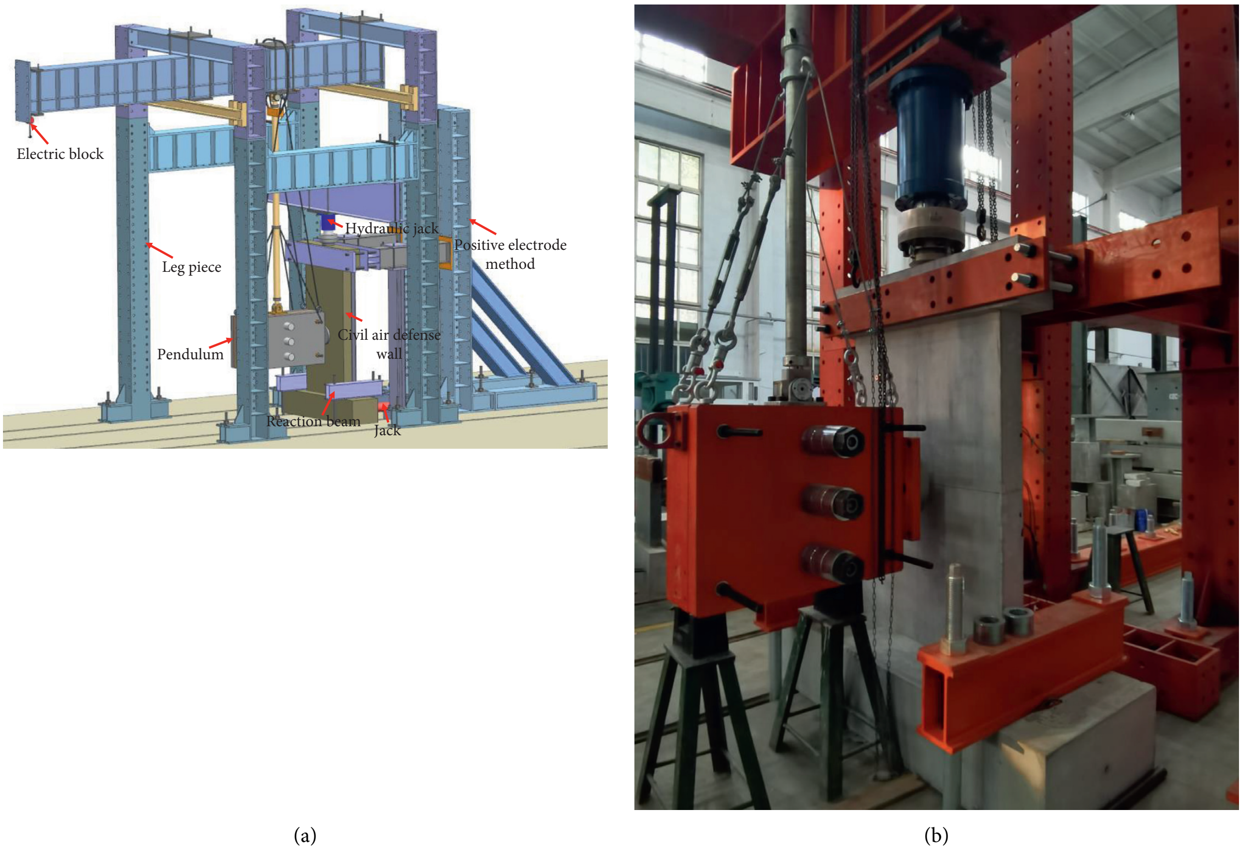


Figure 4: Pendulum impact device. (a) Pendulum impact diagram. (b) Side view of pendulum impact.

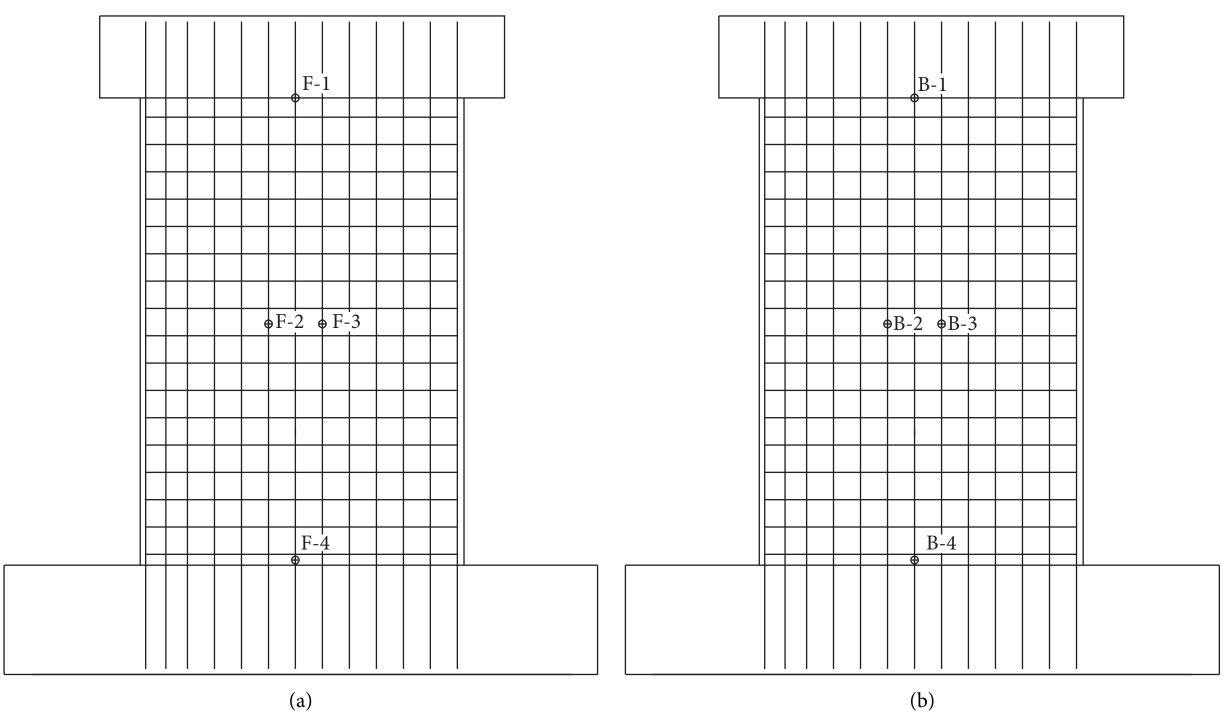


Figure 5: The layout of rebar strain measuring points. (a) Rebar strain measuring points on the impact surface. (b) Rebar strain measuring points on the back.

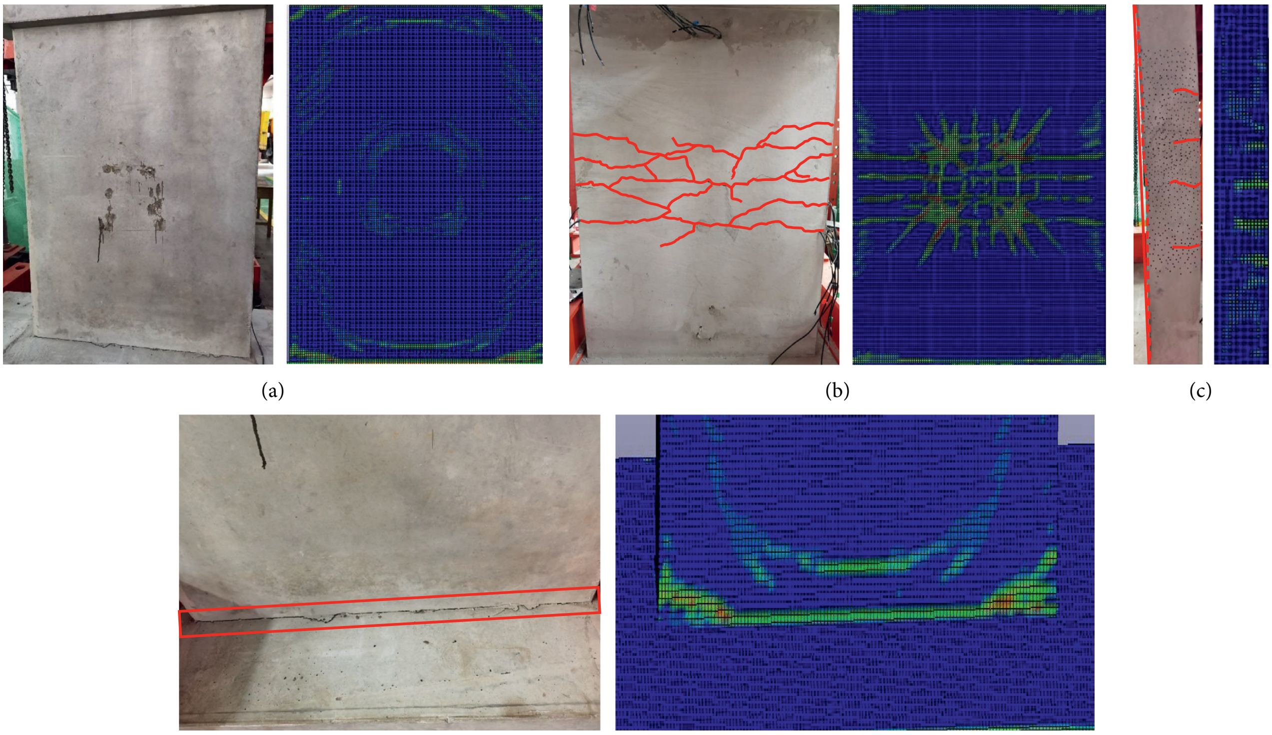


Figure 6: Q-2-0.4 impact damage diagram. (a) Impact surface damage diagram. (b) Back damage diagram. (c) Side damage diagram. (d) Cracks at the bottom of the impact surface.

energy. The back shows bending failure. The concrete cracks in the impact area first occur in horizontal cracks, which is very close to the development of concrete cracks in the numerical simulation results. From Figure 6(c), it can also be seen that the civil air defense engineering shear wall has a slight " bulge" along the impact direction, and there are only small transverse cracks on the side, but there are no penetrating cracks, which further verifies the correctness of the selected steel and concrete material model in simulating the impact resistance of civil air defense engineering shear wall.

4.2. Development of Wall Cracks under Impact. The development process of side crack of civil air defense engineering shear wall impacted by pendulum was recorded by a high-speed camera. As shown in Figure 7, when the pendulum touched the shear wall, the first mid-span side crack appeared at 4 ms. With the increase of impact velocity and the inertia force of the pendulum, the width and length of the side crack increased gradually. During the impact process of civil air defense engineering shear wall, the wall rebounded with the energy consumption of the wall. When the pendulum broke away from the civil air defense engineering shear wall (60 ms), the width of the side crack reached the maximum, and the damage of the civil air defense engineering shear wall was the largest, but there was no penetrating crack.

In order to obtain the crack size of civil air defense engineering shear wall under the impact height of 0.4 m, the side and back cracks near the mid-span position are selected for measurement, as shown in Figure 8(a). The ZBL-F120 concrete crack width measuring instrument is used to amplify the cracks at the above position, and the detailed crack size is shown in Figure 8(b). From Figure 8(b), it can be seen that the bending deformation of the civil air defense engineering shear wall occurs after the impact. The maximum cracks are at the position of side S-3 and back B-2, the maximum crack on the side is 2.16 mm, and the maximum crack on the back is 3.46 mm. The width of the crack can be seen by naked eyes. Most of the cracks are concentrated in the impact center of 500 mm area, the impact center of the crack width is the largest, crack width is almost more than1mm, the upper and bottom of the wall crack are small, crack width is almost less than 1 mm, and the number of cracks in the impact surface is less, which are concentrated in the bottom of the wall.

4.3. Impact Force and Rebar Strain Time-History Curve. Through the impact force and rebar strain data collected by the instrument, the time-history curves of impact force and rebar strain are plotted, as shown in Figure 9. From the time-history curve of impact force in Figure 9(a), it can be seen that when the impact height is 0.4 m, the peak value of the impact force in the test is 921.7 kN, the peak value of the impact force in the finite element simulation is 967.5 kN, and the error is 5%. Within the reasonable error allowable range, the peak duration of the impact force time-history curve is instantaneous, more is the main wave, and the duration is long, which is consistent with the research results in the

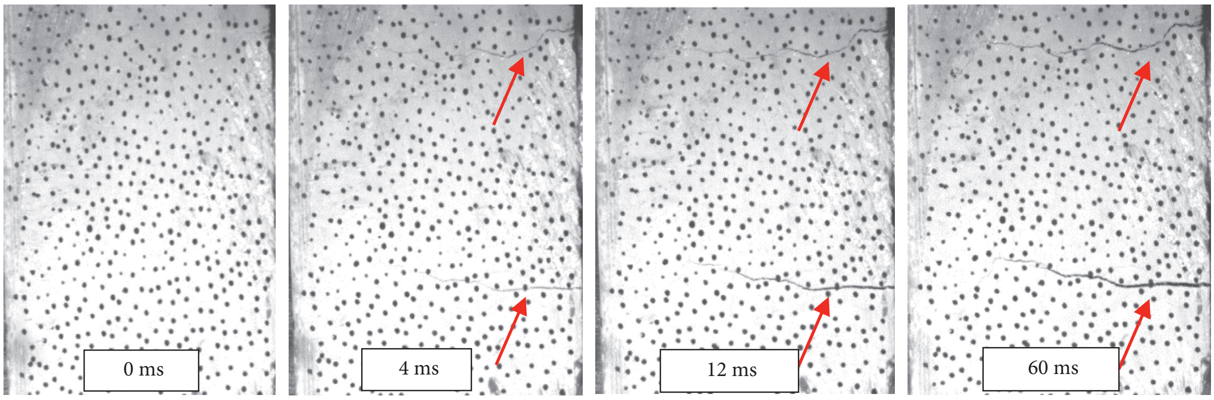
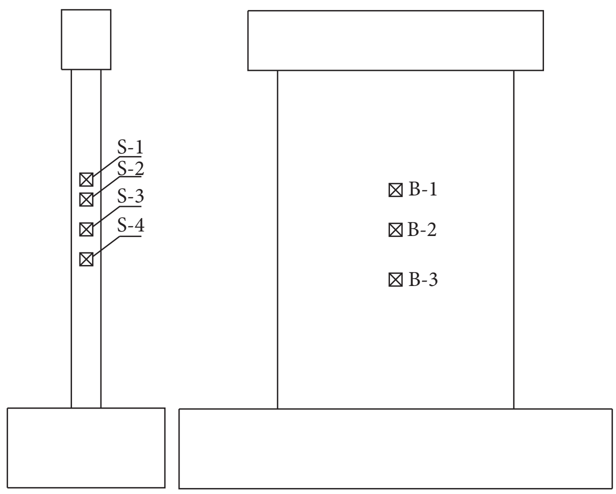
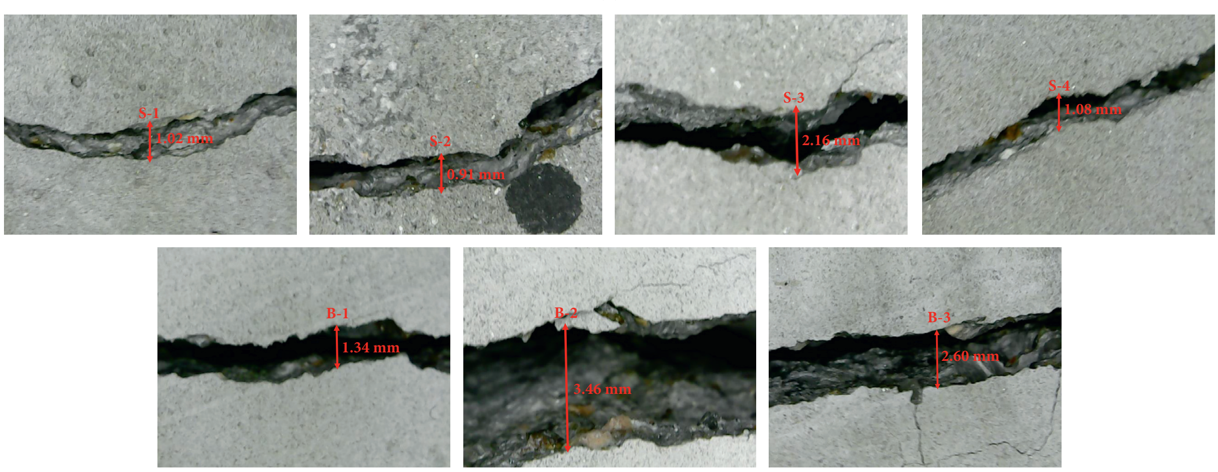


Figure 7: Development process of side cracks.



(a)



(b)

Figure 8: Measurement position and size of cracks. (a) Location map of crack measuring points. (b) Crack size diagram.

literature [37]. It can be seen from the rebar strain in the impact center in Figure 9(b) that when the pendulum impact occurs, the steel on the impact surface appears in a short compression state and then immediately becomes a tensile state. The peak values of the rebar strain on the impact surface and back are about 2000 $\mu\varepsilon$. After the rebar strain reaches the peak value, it shows a downward trend. At this time, the steel does not reach the yield state. With the end of the impact process, the residual strain of the steel is between 800 $\mu\varepsilon$ and 1000 $\mu\varepsilon$. From Figure 9(c), it can be seen that the peak strain of the bottom rebar is about 2600 $\mu\varepsilon$, the peak strain of the upper rebar is about 1600 $\mu\varepsilon$, and the difference

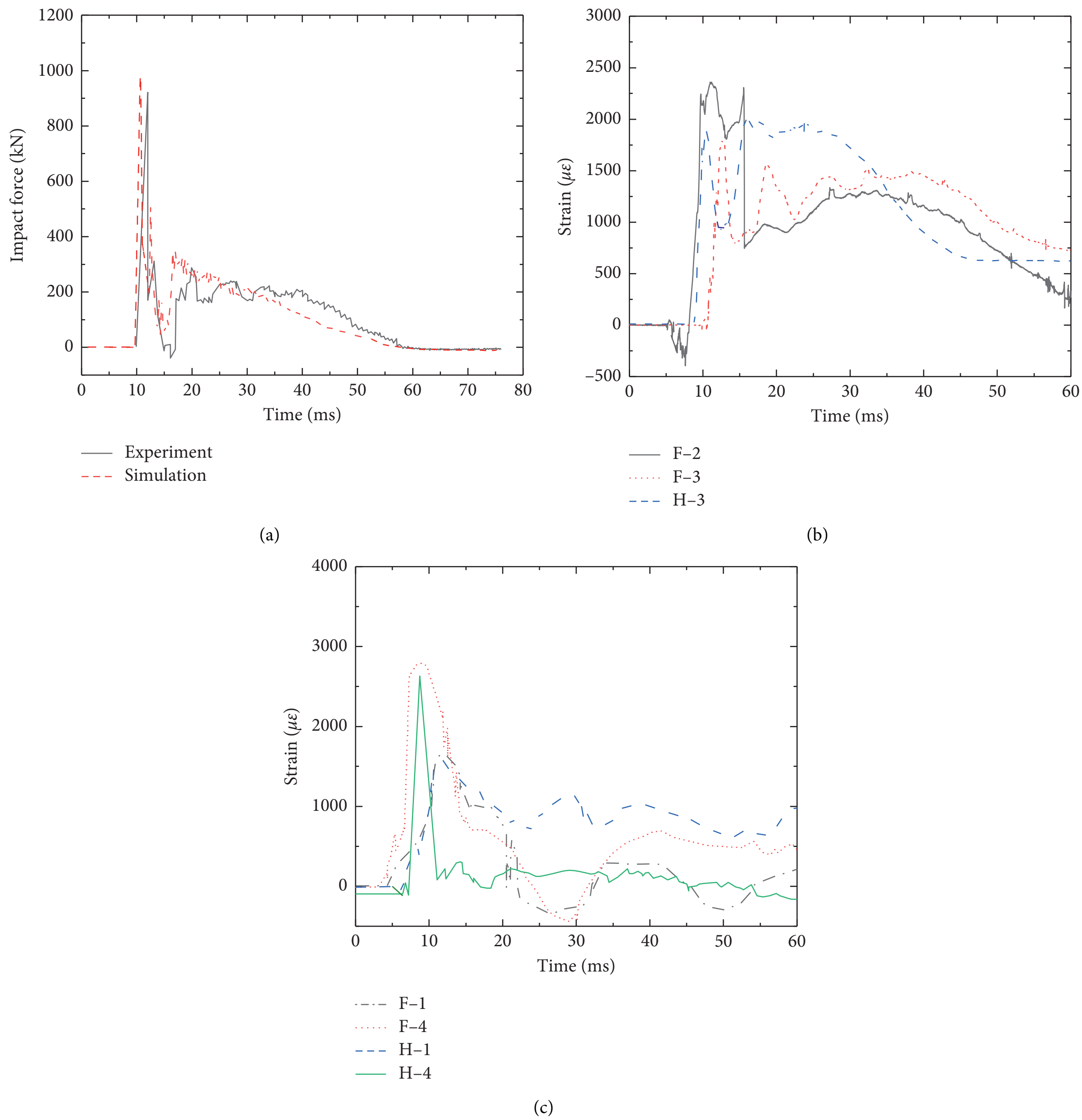


Figure 9: Q-2-0.4 time-history curves of impact force and rebar strain. (a) Impact force time-history curve. (b) The rebar strain at the impact center. (c) The rebar strain of top and bottom.

between the two is 1000 $\mu\varepsilon$, which causes a slender crack in the bottom concrete. The strain of the bottom rebar is larger than that of the upper rebar. The residual strain of the upper and bottom rebar is smaller than that of the impact center. At this time, the rebar is not yielding. The strain of the rebar vibrates up and down with the inertia force.

5. Finite Element Simulation Results Analysis

The pendulum impact finite element model of civil air defense engineering shear wall is established according to the material model and parameters selected in Section 2.1, and the finite element model is modeled according to the boundary constraints of civil air defense engineering shear wall in the test so that the finite element model meets the test conditions as far as possible. The diameter of longitudinal reinforcement and distributed reinforcement of civil air defense engineering shear wall is 8 mm, the diameter of the tie bar is 6 mm, the tie bar is arranged in plum blossom, the distance between longitudinal reinforcement and distributed reinforcement is 100 mm, the distance between plum blossom tie bar is 200 mm, the thickness of the concrete protective layer is 30 mm, and the finite element model is shown in Figure 10.

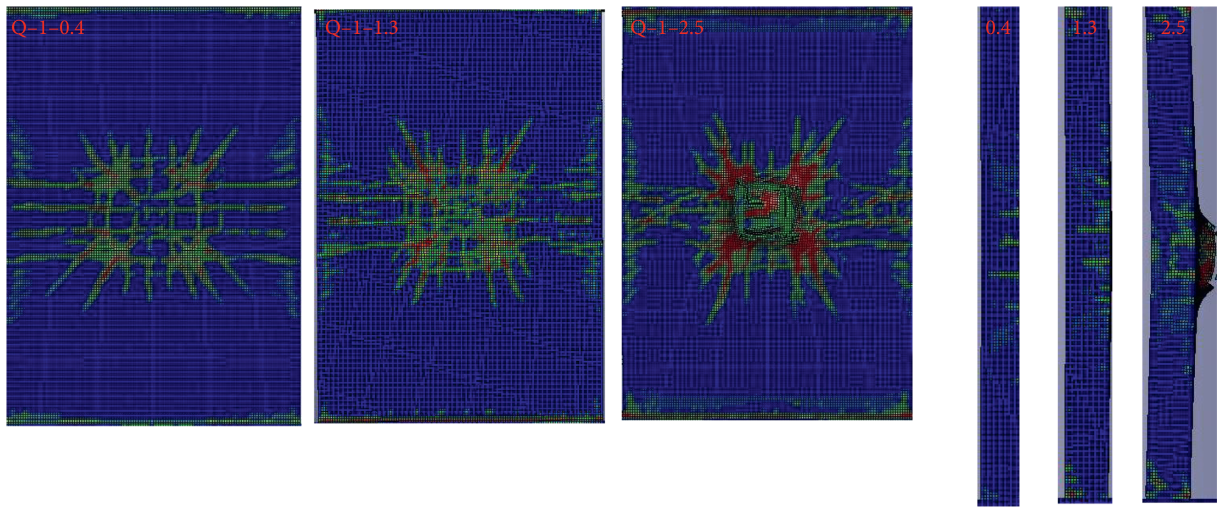
(a) (b)

Figure 10: Comparison between finite element model and test device. (a) Test boundary conditions. (b) Boundary conditions of finite element model.

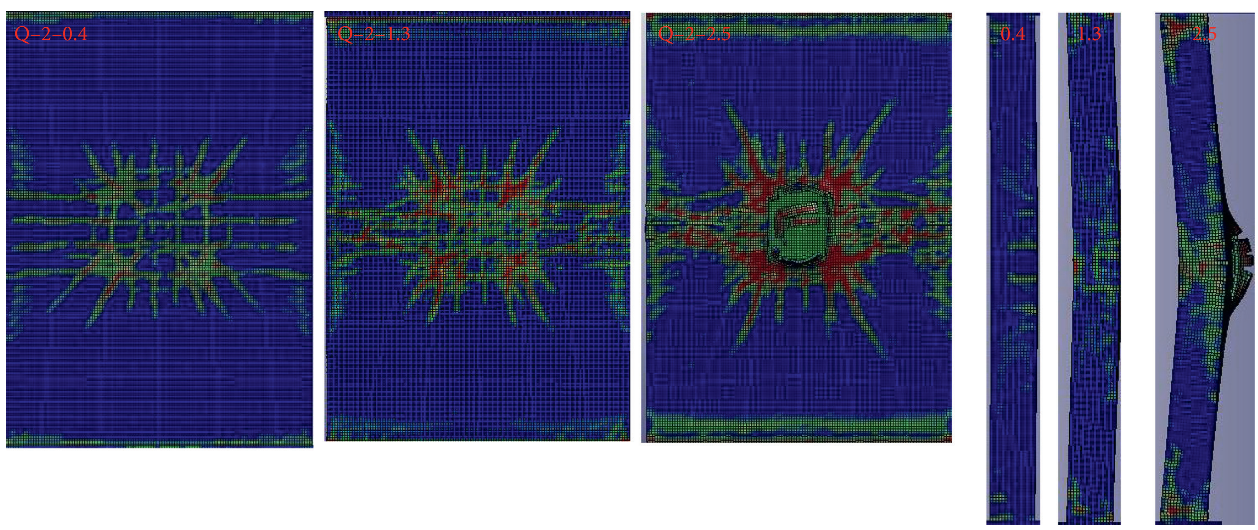
5.1. Influence of Impact Height. Figure 11 compares the influence of different impact heights on the damage of civil air defense engineering shear wall, the red in the figure indicates the wall crack width and damage degree, and the redder the color, the greater the damage degree. It can be seen from the back damage figure that, with the increase of impact height, the number of concrete cracks in the back of the civil air defense engineering shear wall increases significantly, and the edge of the civil air defense engineering shear wall also appears small cracks. The damage of civil air defense engineering shear wall begins to focus on the impact area, there is no overall failure pattern, and more inclined cracks appear. Obvious deflection deformation of civil air defense engineering shear wall can be seen from the side damage figure. With the increase of impact height, more cracks appear at the top and root of the civil air defense engineering shear wall, and even concrete spalling occurs in the impact area, which indicates that the civil air defense engineering shear wall has lost its protection and bearing capacity. Therefore, with the increase of the impact height, the damage degree of the civil air defense engineering shear wall is also increased, but there will be no overall damage and more and more concentration in the damage of the impact area, which provides certain guiding significance for the next civil air defense engineering shear wall protection and transformation.

Figure 12 compares the influence of different impact heights on the mid-span displacement of the civil air defense engineering shear wall under the same pendulum mass. As can be seen from Figure 12, when the impact height increases from 0.4 m to 2.5 m, the displacement of the wall increases the fastest, the maximum displacement increases from 12.02 mm to 71.85 mm, which is nearly expanded by 5 times, and the maximum residual displacement increases by nearly 7 times. This shows that, with the increase of the impact height, when the wall is impacted by the pendulum, the elastic process time of the concrete is shortened, and the concrete directly enters the plastic state. The concrete quickly cracks and finally completely cracks, resulting in irreversible residual deformation and loss of protective ability. Therefore, high-strength concrete can be used to improve the overall stiffness of the civil air defense engineering shear wall structure and reduce the mid-span displacement of the civil air defense engineering shear wall.

It can be seen from the time-history curve of the impact energy of the civil air defense engineering shear wall in Figure 13 that, in the process of pendulum impact on the wall, the kinetic energy and internal energy in the structural system are transformed into each other, and the kinetic energy in the system is transformed into the internal energy of the wall. With the contact between the pendulum and the wall, the internal energy of the civil air defense engineering shear wall gradually increases, and the internal energy does not increase after reaching the peak value. At this time, the kinetic energy tends to 0, and the civil air defense engineering shear wall tends to be static from the motion state. With the increase of pendulum impact height, the kinetic energy input into the civil air defense engineering shear wall is larger, and the kinetic energy is finally converted into internal energy for dissipation. The converted internal energy is lower than the kinetic energy, indicating that there is energy loss in the process of pendulum impact. It can be seen from Figure 14 that when the pendulum mass is 1 ton, the proportion of absorbed energy of concrete decreases from 39.67% to 17.68% with the increase of impact height, and the proportion of absorbed energy of steel increases by 21.99%. When the pendulum mass is 2 tons, the impact height increases from 0.4 m to 2.5 m, and the absorbed energy of concrete decreases



(a)



(b)

Figure 11: Damage diagram of the shear wall at different impact heights. (a) Q-1- X back and side damage figure. (b) Q-2 - X back and side damage figure.

gradually, accounting for 17.39% in the whole energy conversion process. When local damage occurs to the wall, the energy consumption of concrete does not increase. This shows that, with the increase of impact height, the energy consumption proportion of steel and concrete changes significantly, and the energy absorption of concrete decreases significantly. When the concrete of civil air defense engineering shear wall cracks or breaks, the energy input into the wall is finally dissipated by steel, and the proportion of energy absorbed by steel is gradually increased.

The strain of longitudinal reinforcement in the impact center area of civil air defense engineering shear wall is selected, and the time-history curve of reinforcement strain is drawn as shown in Figure 15. With the same pendulum mass and the increase of pendulum impact height, the longitudinal reinforcement on the back of the wall is always in a tensile state, and the maximum peak strain of the steel bar is 19000 $\mu\varepsilon$, indicating that the steel bar at the measuring point is fully yielding. After the peak strain decreases, the residual strain is generated in a certain range, and the maximum strain is 17000 $\mu\varepsilon$. The peak strain of the steel bars on the impact surface of the wall is more than 1700 $\mu\varepsilon$, and the maximum strain reaches 3400 $\mu\varepsilon$. Compared with the residual strain of the steel bars on the back, the residual strain of the steel bars on the impact surface is smaller and fluctuates between 500 $\mu\varepsilon$ and 1800 $\mu\varepsilon$, and the maximum residual strain is 1800 $\mu\varepsilon$. This shows that the damage degree of the impact surface of the wall is lower than that of the concrete on the back, which is consistent with the damage diagram of the wall simulated by Figures 13 and 16. Therefore, we can get the fact that the back reinforcement strain is greater than the impact surface reinforcement strain. With the crushing of the back concrete, the strain of reinforcement reaches the ultimate strain. When the impact height continues to increase, the longitudinal reinforcement will be broken.

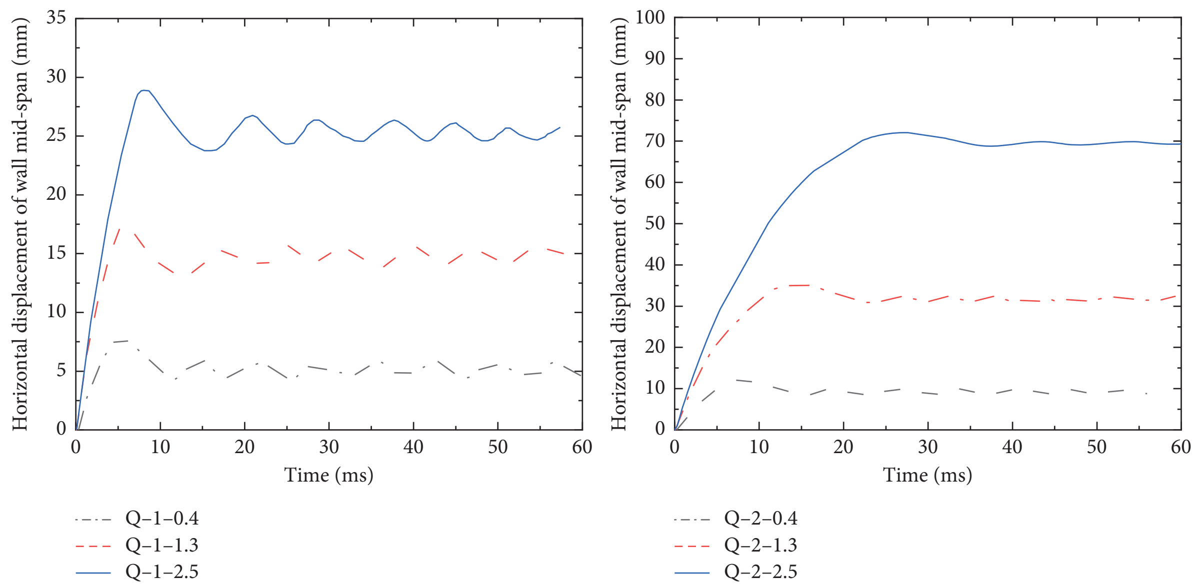


Figure 12: Time-history curves of mid-span horizontal displacement under different impact heights.

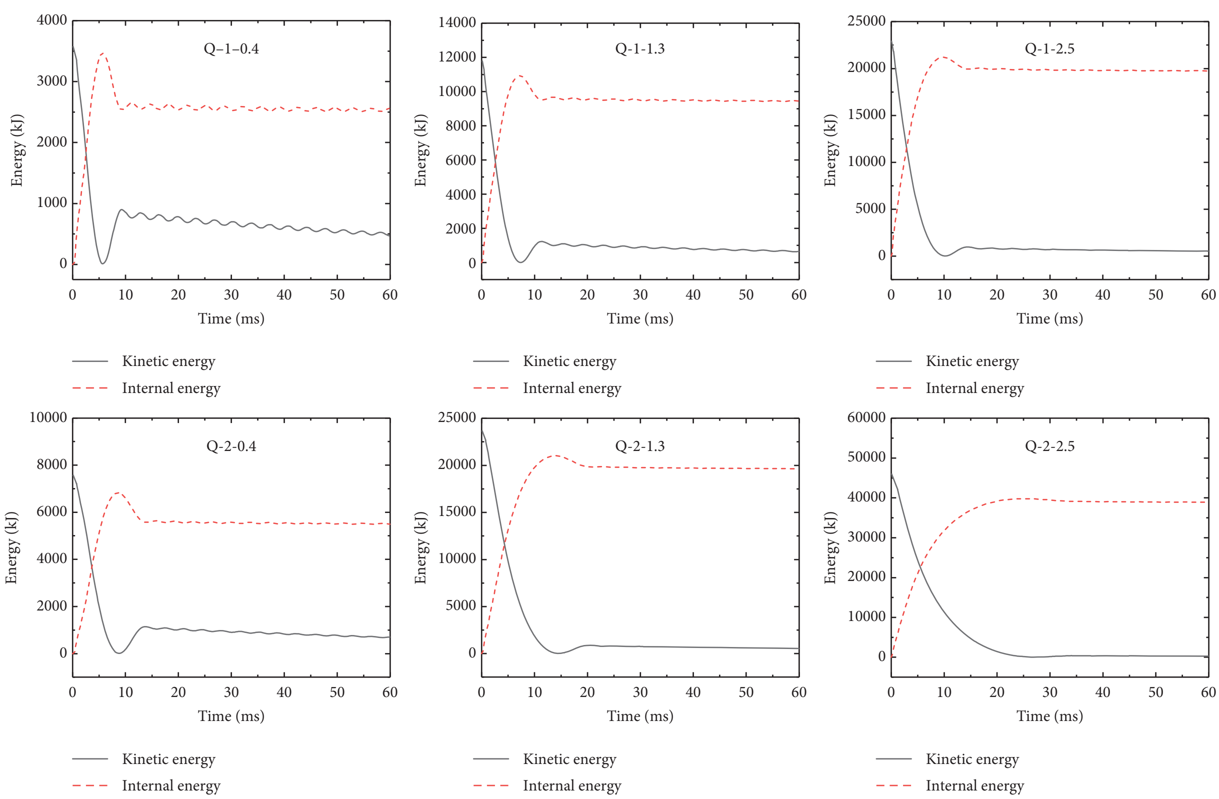


Figure 13: Energy conversion curve of the shear wall under different impact heights.

5.2. Influence of Pendulum Mass. Figures 17 and 18 compare the influence of different pendulum mass on the destruction of civil air defense engineering shear wall, the red in the figure indicates the wall crack width and damage degree, and the redder the color, the greater the damage degree. Changing the pendulum mass, from 1 ton to 2 tons, with the increase of mass, the number of concrete horizontal cracks in the back of civil air defense engineering shear wall increases, but the increase is less. It has a great influence on the concrete cracks of the impact surface. The increase of the mass leads to the overall fine cracks in the impact surface but is still concentrated in the impact area. Therefore, the increase of pendulum mass has little effect on the damage degree of the shear wall back of civil air defense engineering, and the damage to the impact surface increases.

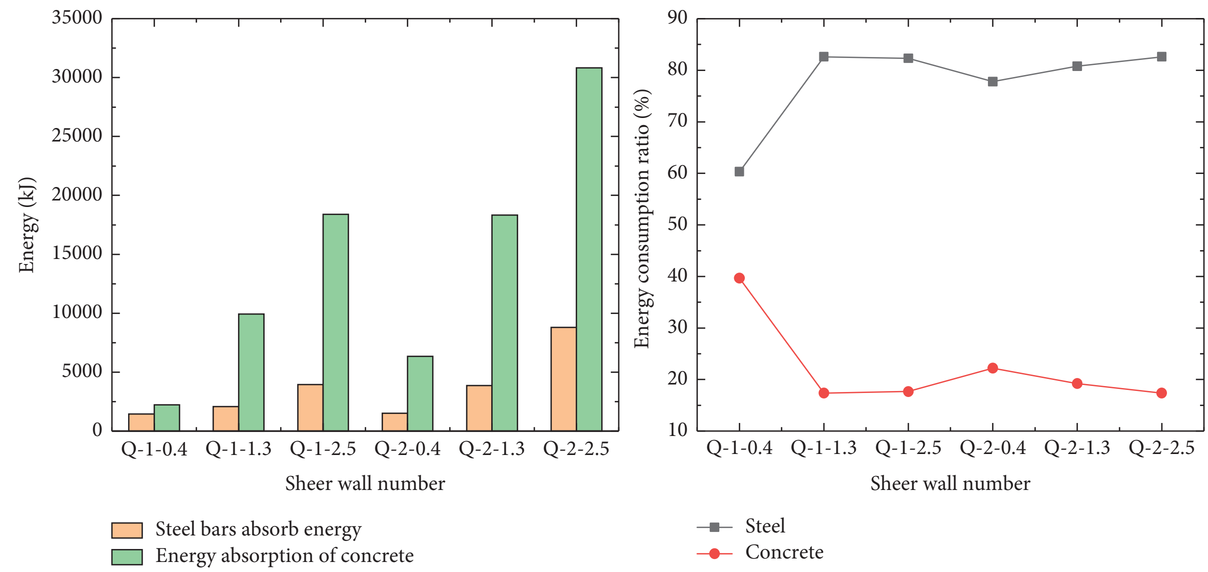


Figure 14: Energy proportion diagram of each part of the wall.

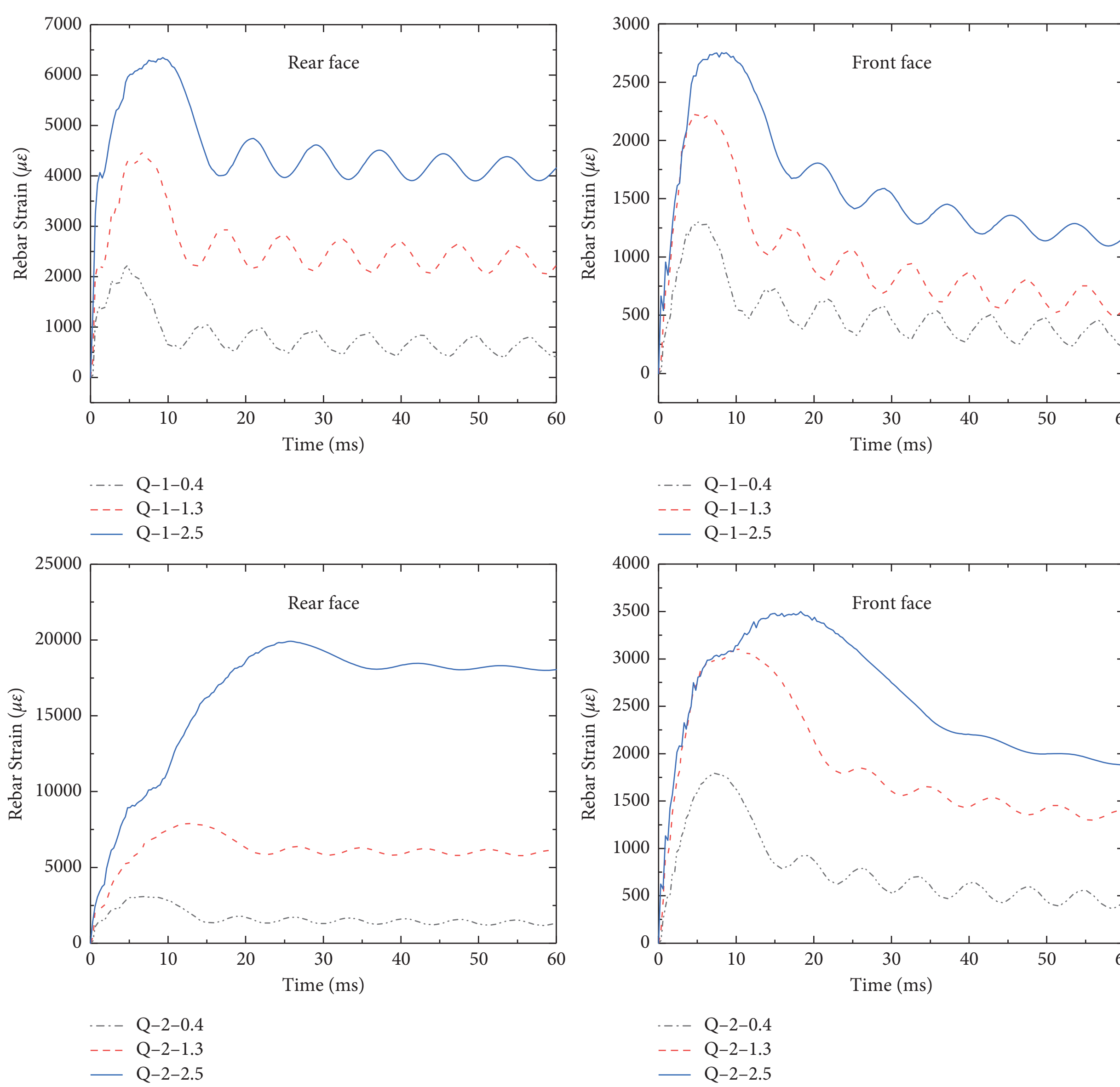
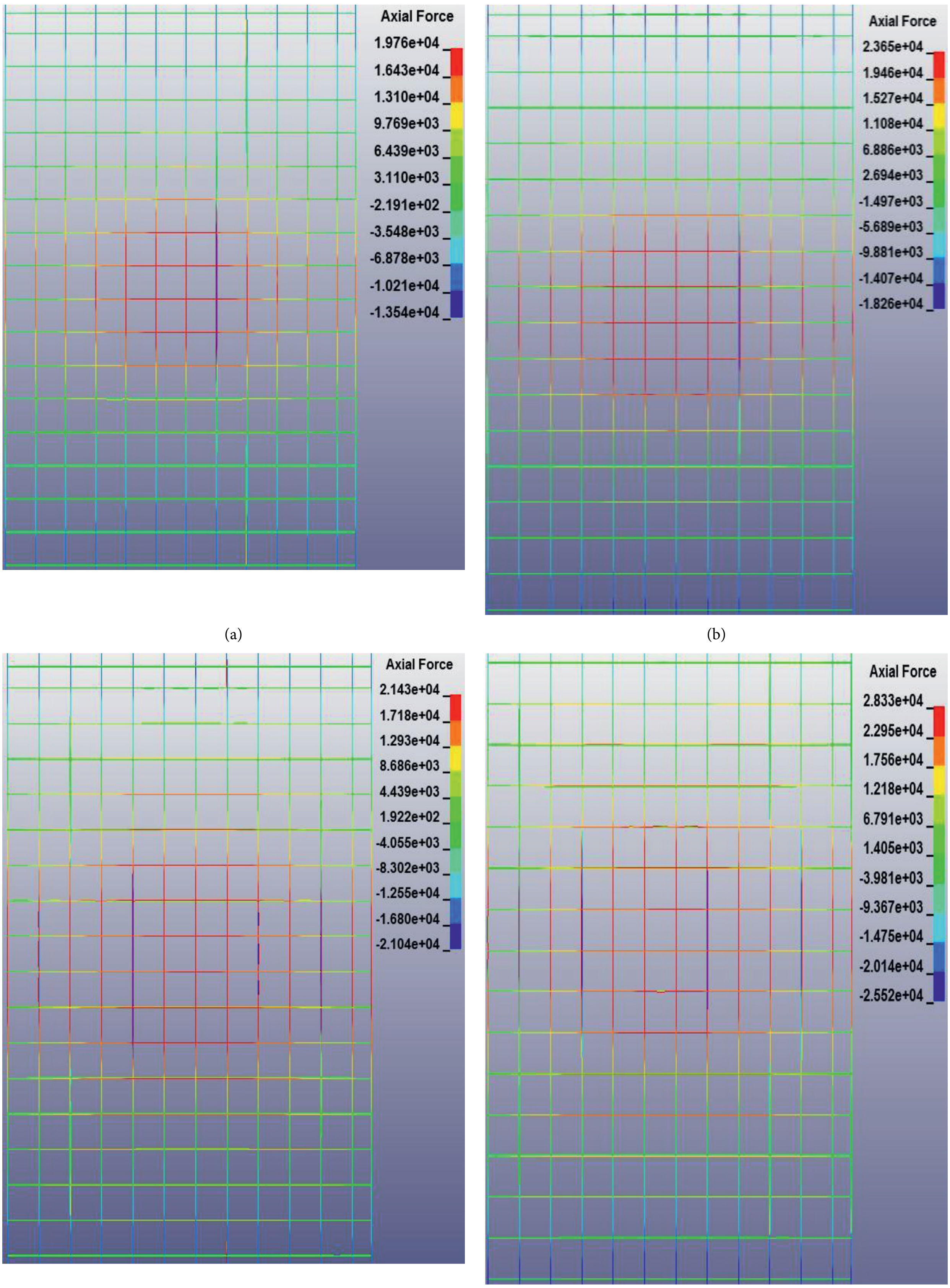
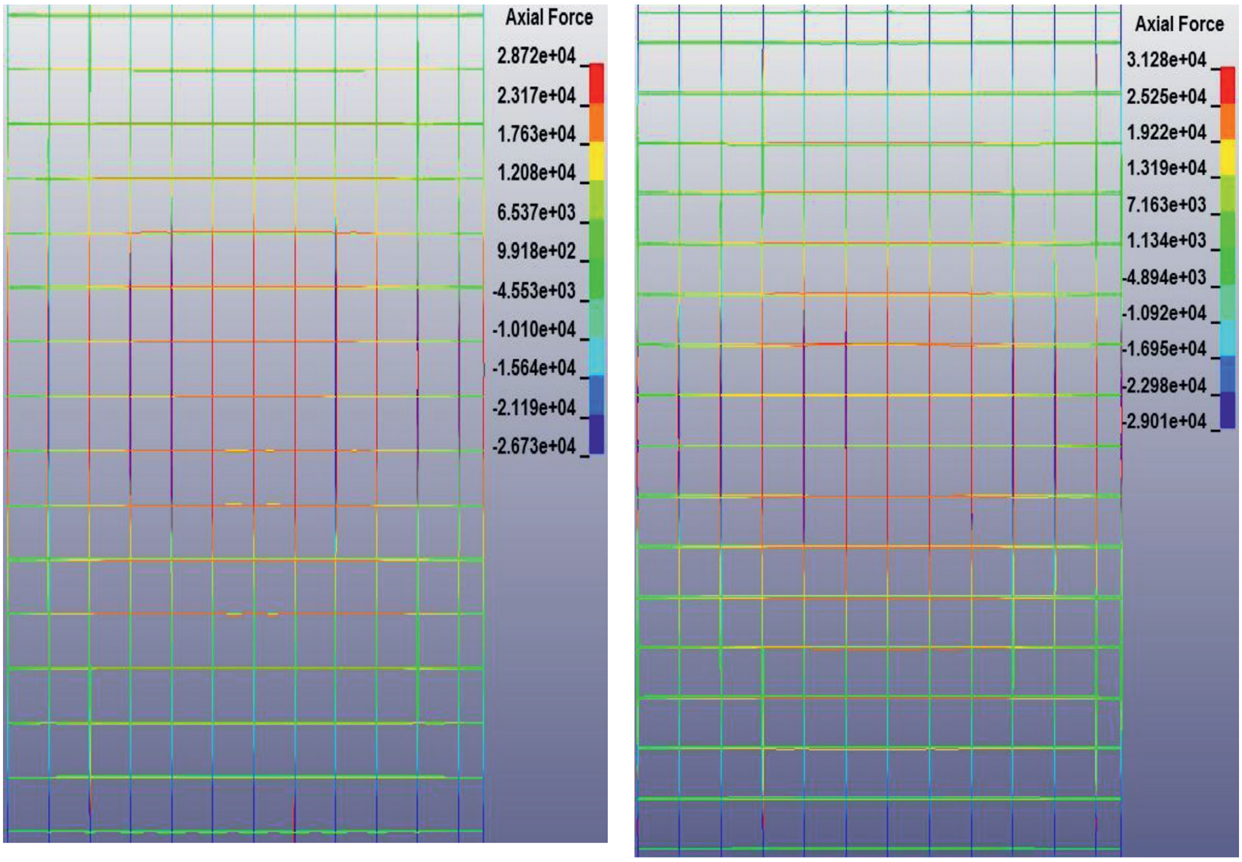


Figure 15: Time-history curve of steel strain in impact center of shear wall.



(a) (b) (c) (d)

Figure 16: Continued.



(e) (f)

Figure 16: Axial force contours of the rebars in the rear face. (a) Q-1-0.4. (b) Q-2-0.4. (c) Q-1-1.3. (d) Q-2-1.3. (e) Q-1-2.5 (f) Q-2-2.5.

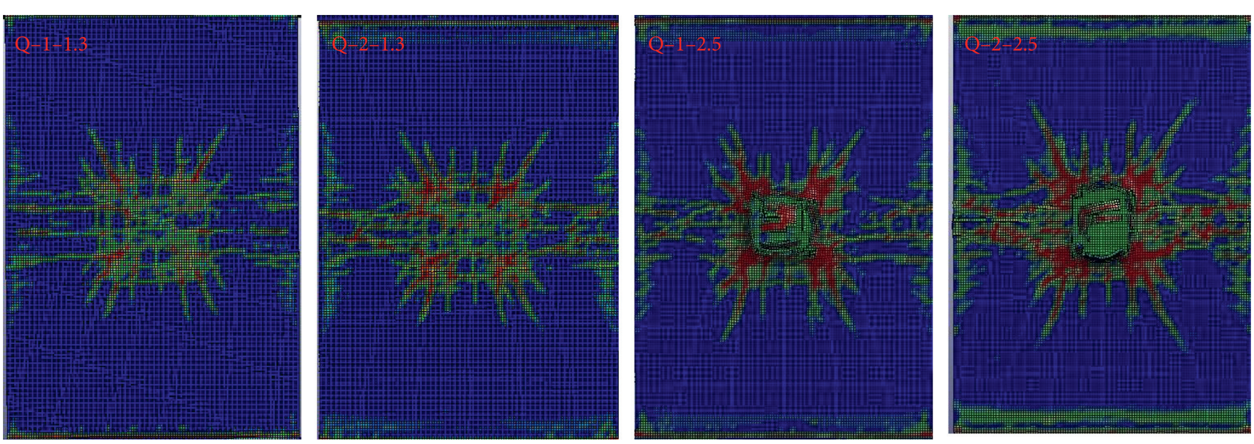


Figure 17: Comparison of back damage under different pendulum mass.

Figure 19 compares the influence of different pendulum mass on the mid-span horizontal displacement of civil air defense engineering shear wall at the same impact height. When the impact height is 1.3 m and the pendulum mass increases from 1 ton to 2 tons, the peak displacement increases by 17.77 mm, the residual displacement increases by 17.62 mm, the wall produces a large deflection deformation, and the back concrete is seriously damaged. When the impact height is 2.5 m, with the increase of the pendulum mass, the impact surface and back surface of the wall have large deformation, and the residual displacement increases by 45.07 mm at most. The concrete on the back surface is seriously cracked, resulting in bending failure of the wall. At the same impact height, the impact mass of the pendulum changes, and the corresponding impact energy also changes. However, the total energy absorbed by concrete and steel is certain. When the impact energy exceeds the total energy absorbed by concrete and steel, it will lead to an increase in

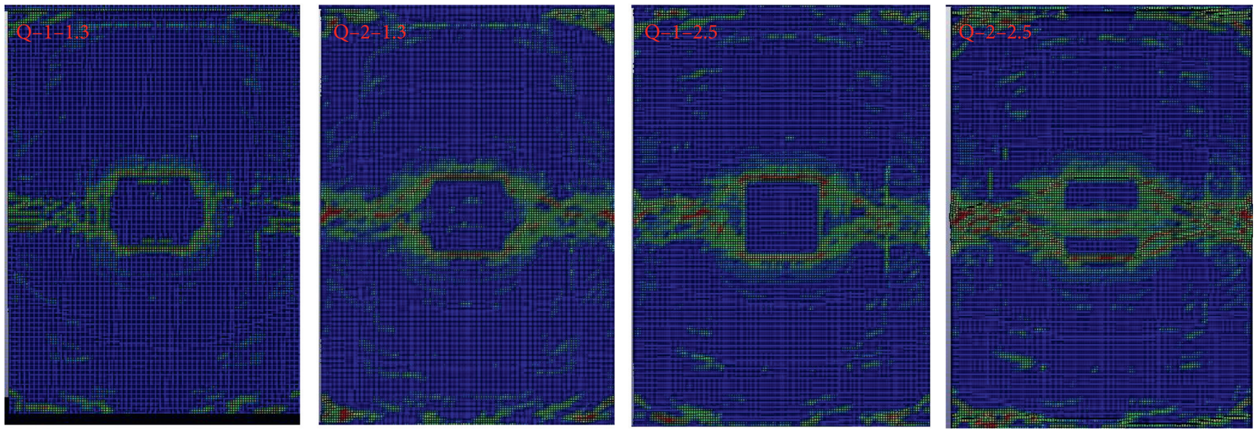


Figure 18: Comparison of impact surface damage under different pendulum mass.

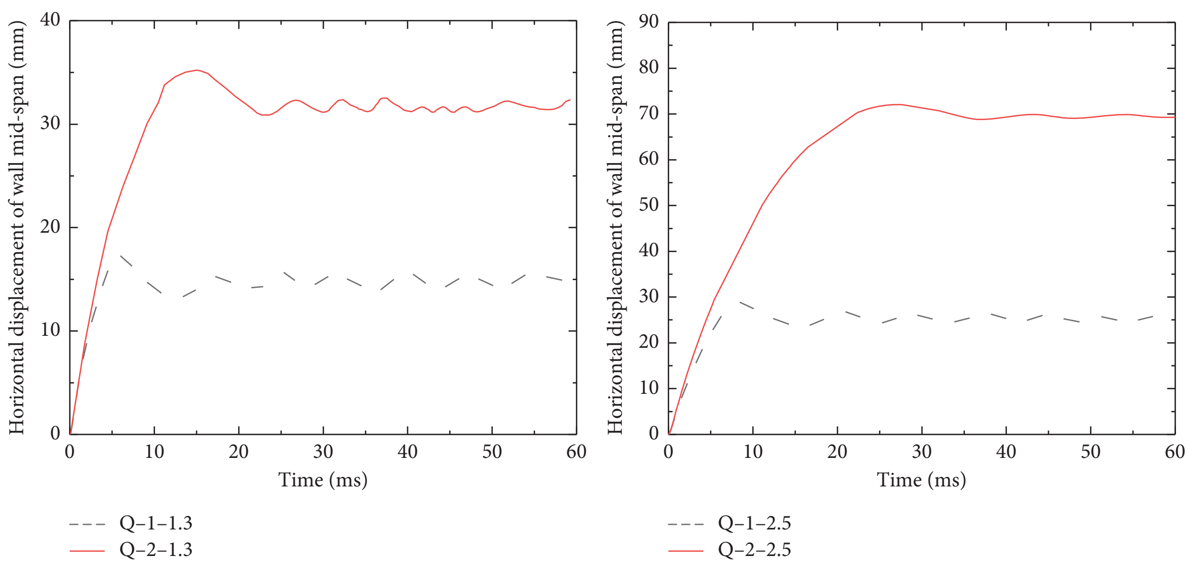


Figure 19: Time-history curves of horizontal displacement of wall span under different pendulum mass.

the mid-span displacement, which cannot be restored to the elastic-plastic stage. The final manifestation is that the concrete is broken and the rebar is broken.

From the axial force of the back reinforcement shown in Figure 16, it can be seen that the range of the axial force of the back reinforcement is 13 kN–31 kN. With the increase of the pendulum mass, the axial force of the back reinforcement increases significantly, and the bending deformation of the back reinforcement along the impact direction appears. At the same impact height, with the increase of the pendulum mass, the range of the axial force of the back reinforcement is expanding. Combining Figures 16(e) and 16(f) with the damage diagram of the back concrete in Figure 17, it can be seen that, with the increase of the axial force of the back reinforcement, the back concrete is also broken. Through the size and contour range of the axial force of the back reinforcement, it can be obtained that the expansion of the axial force range of the reinforcement will cause the cracking and crushing of the back concrete.

5.3. Influence of Impact times. In order to obtain the influence of impact times on the impact resistance of civil air defense engineering shear walls, repeated impact tests were conducted on the same wall. Firstly, the impact test with a pendulum mass of 2tons and impact height of 0.25 m is carried out. The results are shown in Figure 20. There are only two small cracks on the back of the civil air defense engineering shear wall, and no concrete penetrating cracks appear. There is almost no damage to the steel and concrete, and the civil air defense engineering shear wall can still be used normally. Then, under the same pendulum mass, the impact height is increased to 0.5 meters, the results are shown in Figure 21, the back crack of the civil air defense engineering shear wall is centered on the impact area, and it is radioactive to crack around. The side of the civil air defense engineering shear wall is cracked, and the deflection of the wall is visible. Through the analysis of the crack width and deflection at this time, the civil air defense engineering shear wall does not reach the ultimate bearing capacity state, but the

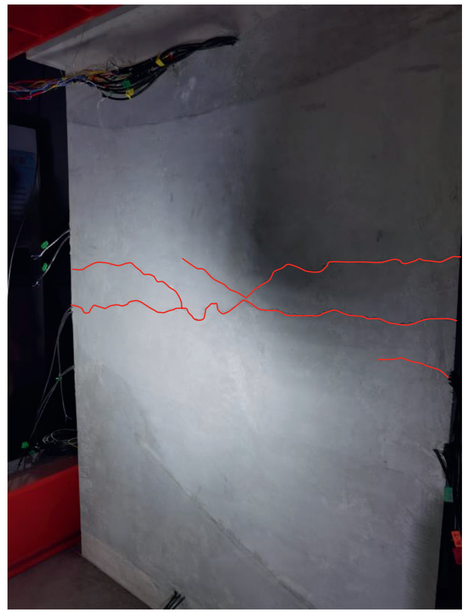


Figure 20: Q-2-0.25 back damage diagram.

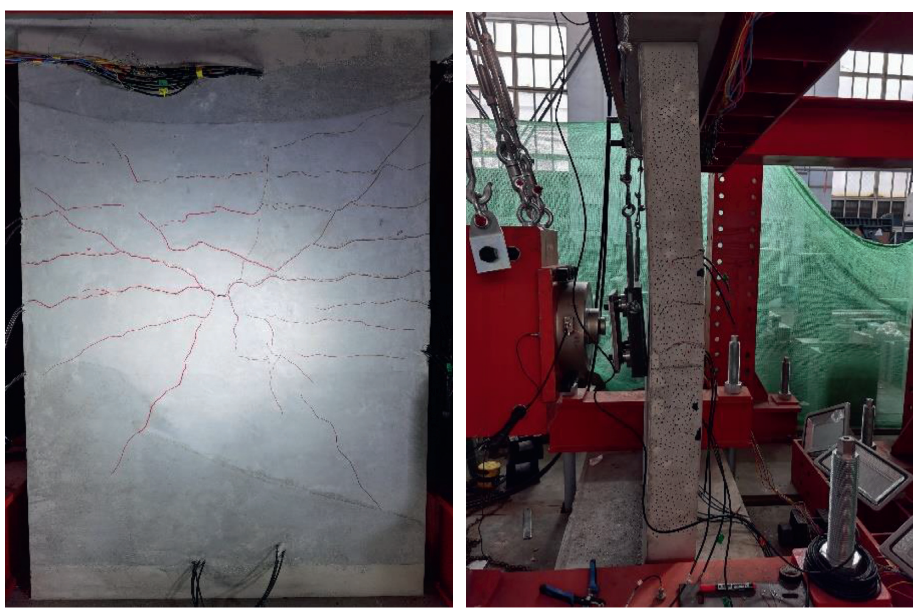


Figure 21: Q-2-0.5 back and side damage diagram.

protective ability of the civil air defense engineering shear wall has declined, and the cumulative damage has occurred.

Finally, the impact height is increased to 2 m. At this time, the damage of the civil air defense engineering shear wall is shown in Figure 22. The mid-span damage of the wall appears on the impact surface, the concrete is peeled off, and the rebar is exposed and bent. The steel plate gasket is directly embedded in the concrete. The concrete in the impact area of the back of the civil air defense engineering shear wall is seriously dropped, and the longitudinal tensile rebar and the tie bar reach the ultimate strength, but there is no rebar fracture. The concrete in the mid-span of the side of the civil air defense engineering shear wall is also broken, and obvious deflection deformation occurs. Amplifying the impact surface and the bottom of the back, it can be seen that large cracks are generated and even broken. At this time, it can be obtained that the civil air defense engineering shear wall has lost its protective ability and cannot continue to use. Therefore, the impact times have a great influence on the impact resistance of the civil air defense engineering shear wall. With the increase of the impact times, the yield of the rebar leads to the repair delay of the civil air defense engineering shear wall after the impact load, and the damage of the civil air defense engineering shear wall is

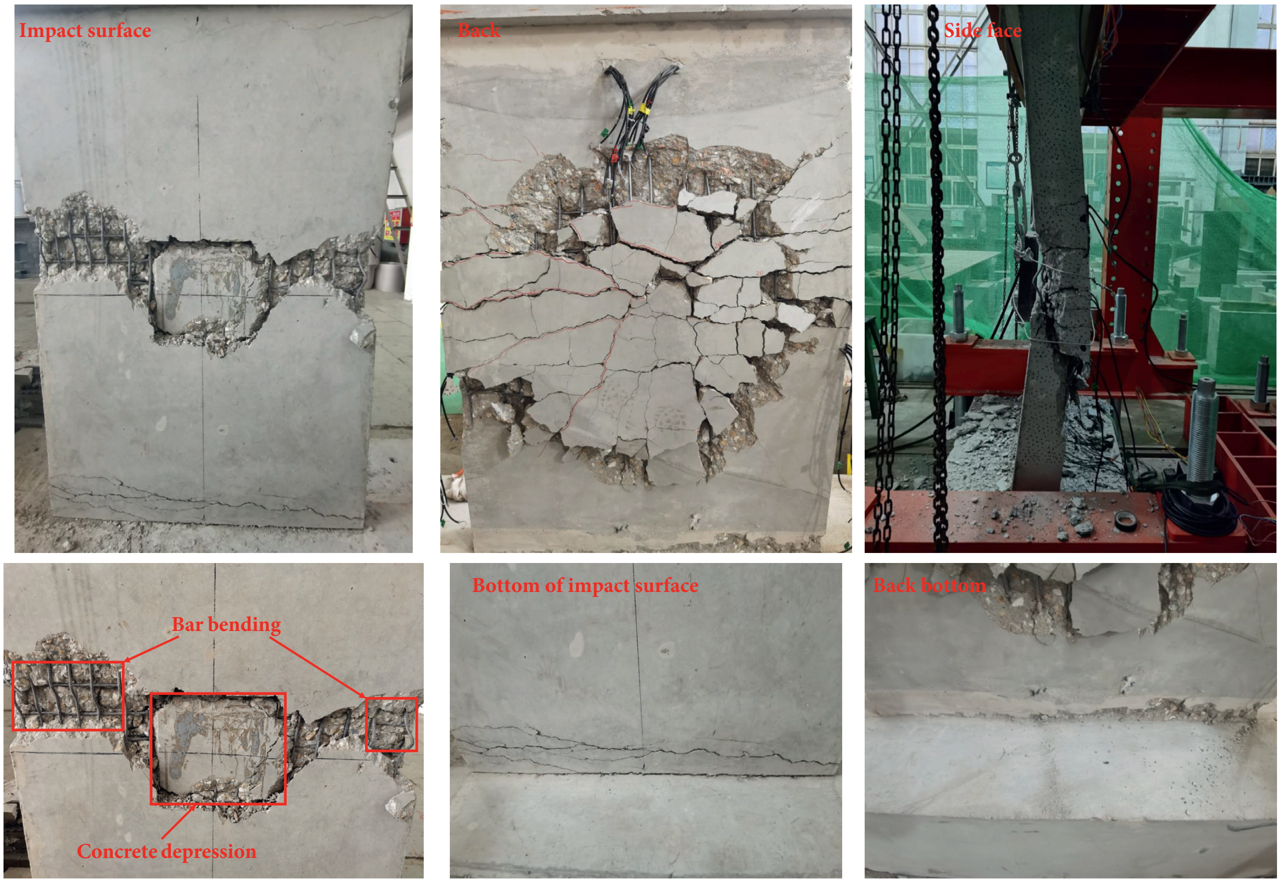


Figure 22: Q-2-2.0 failure diagram.

Table 5: Simulation data of central displacement and impact energy of civil air defense engineering shear wall.

Shear wall number of civil air defense engineering	The maximum displacement wall center (mm)	Residual displacement of wall center (mm)	Displacement ratio = residual displacement of wall center/the maximum displacement wall center	Impact energy (kJ)
Q-1-0.4	7.96	4.42	0.56	3.92
Q-1-1.3	17.25	13.27	0.77	12.74
Q-1-2.5	28.85	23.77	0.82	24.50
Q-2-0.25				4.90
Q-2-0.4	12.02	8.53	0.71	7.84
Q-2-0.5				9.80
Q-2-1.3	35.02	30.89	0.88	25.48
Q-2-2.0				39.20
Q-2-2.5	71.85	68.84	0.96	49.00

Note. The values of Q-2-0.25, Q-2-0.5, and Q-2-2.0 in the table are not indicated due to multiple shocks to the same wall.

gradually accumulated. The excessive plastic deformation of the rebar under the impact load will lead to permanent residual displacement and aggravate local damage, resulting in the loss of usability and stability of the civil air defense engineering shear wall and finally the loss of the protective ability. It is suggested that when the concrete cracks of the civil air defense engineering shear wall are large, it should not continue to use and should be protected and strengthened to avoid collapse.

5.4. Impact Energy Simulation Results Analysis. It can be seen from Table 5 that when the impact energy increases, the residual displacement of civil air defense engineering shear wall increases significantly, and the energy consumption of steel and concrete increases. When the impact energy reaches 49 kJ, the displacement ratio even reaches 0.96, indicating that the concrete at this time quickly reaches the plastic state, and the concrete cracks and finally breaks. Based on the magnitude of impact energy, the recommended displacement ratio of the civil air defense engineering shear wall that loses the protection ability is proposed. It is suggested that the displacement ratio is less than 0.7, and the civil air defense engineering shear wall can exert the protection ability.

6. Conclusion

In this paper, six groups of simulation analysis and two groups of experimental research on the impact resistance of civil air defense engineering shear walls were carried out. The finite element analysis of civil air defense engineering shear walls was carried out by ANSYS/LS-DYNA, and the correctness of the material model was verified. The influence of impact height, pendulum mass, and impact times on the impact resistance of civil air defense engineering shear walls was analyzed. On this basis, it has guiding significance for the next study on the resistance of civil air defense engineering shear walls to impact load. The main conclusions of this paper are as follows:

(1) The correctness of the selected concrete and steel model to simulate the impact resistance of civil air defense engineering shear wall is verified, which can accurately simulate the concrete damage process, the mid-span horizontal displacement change process of the wall, and other dynamic responses.

(2) Under the same conditions, when the impact height increases, large oblique cracks appear on the back of the civil air defense engineering shear wall. With the increase of impact height, the maximum displacement of the wall increases by 59.83 mm, resulting in irreversible residual deformation, the maximum residual displacement is 68.84 mm, and the impact surface is also damaged by concrete. The failure mode of the civil air defense engineering shear wall tends to be a local failure, and it is no longer the overall damage.

(3) Changing the pendulum mass, when the pendulum mass increases from 1 ton to 2 tons, the number of horizontal cracks in the back of the civil air defense engineering shear wall increases, and the number of vertical cracks decreases. The increase of the pendulum mass will lead to the increase of the damage degree of the wall. However, the failure pattern of the civil air defense engineering shear wall is still a local failure. The pendulum mass is one of the factors that lead to the local failure of the civil air defense engineering shear wall.

(4) With the increase of impact times, the impact resistance of the civil air defense engineering shear wall gradually decreases. The more impact times are, the greater the damage accumulation of the civil air defense engineering shear wall is, and the ability to resist the impact load is greatly reduced, which will eventually directly lead to the collapse of the civil air defense engineering shear wall. The increase of impact times will be one of the main factors affecting the impact resistance of the civil air defense engineering shear wall.

Data Availability

The datasets used and analyzed during the study are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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