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Research Article

Numerical Simulation Study of Progressive Collapse of Reinforced Concrete Frames with Masonry Infill Walls under Blast Loading

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The influence of masonry infill walls on the progressive collapse performance of reinforced concrete (RC) frame structures was investigated in this paper, using a nonlinear dynamic analysis approach. Based on ANSYS/LS-DYNA finite element software, two finite element models of RC frame structures with and without masonry infilled walls were established. Then, the collapse modes of the two RC frame structure models were analyzed for different scaled distance blast loads, different locations of column damage, and different span numbers. The results show that with the increase of explosive amount, the collapse degree of the structure is more serious in the same time. Under the condition of destroying the outermost central column, the degree of progressive collapse of the RC frame model with infilled walls in the same time is lower than that of the RC frame model without infilled walls. The RC frame model with infilled walls is more resistant to collapse when the outermost side columns are damaged. With the increase of span number, the structure is more likely to be damaged and collapsed.

1. Introduction

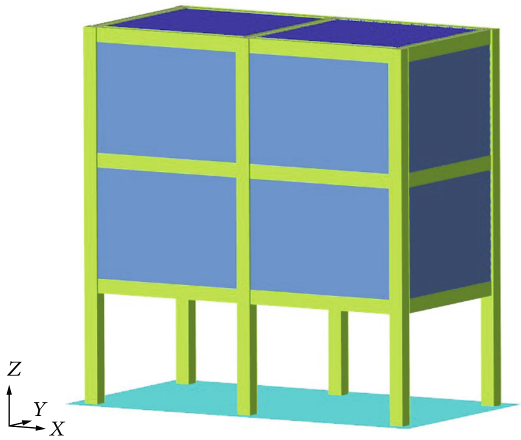
The progressive collapse of the structure refers to the phenomenon that under the action of unexpected loads, such as earthquake, explosion, fire, impact, and terrorist attacks, the structure is partially destroyed or some substructures are destroyed, and the redistribution of the loads leads to a chain reaction, which leads to the spread of destruction and leads to the complete collapse of the structure. The collapse of buildings often causes serious casualties and economic losses. The collapse of apartment buildings in Ronan Point, England in 1968 and the collapse of the Twin Towers of the World Trade Center in 2001 made people begin to pay attention to the progressive collapse of buildings. GSA (General Services Administration) of the United States and DOD (United States Department of Defense) of the United States put forward corresponding design criteria to prevent the progressive collapse of buildings, such as GSA2016 and DOD.UFC4-023-03, which provide methods for the anticollapse design of structures.

The collapse behaviors of concrete frame structures, steel frames, and other structures have been investigated extensively by domestic and foreign scholars in recent years through experiments as well as numerical simulations for comparative purposes. Li et al. [1] calculated the nonlinear dynamic progressive anticollapse demand of RC frame structure under catenary mechanism based on energy method, and verified the proposed theoretical framework by numerical examples. Deng et al. [2] designed different frames for comparative experiments in order to assess the effect of different span-to-depth ratios as well as concrete strength on the behavior of RC frames resisting progressive collapse. It was found that the span-depth ratio had a significant influence on the arching, while the high-strength concrete had a negative influence on the catenary capacity. Yu and Tan [3] put forward a macro-bar stress-slip model, and used the macronumerical model to analyze the influence of boundary conditions, the depth of steel bars and beams on the middle column removal test of reinforced concrete composite structures. Feng et al. [4] validated their proposed numerical simulation framework for a precast reinforced concrete structure by designing a ten-storey precast RC structure and analytically investigated the effect of different parameters on the collapse resistance mechanism of the structure. Alshaikh et al. [5] verified the reliability of the proposed numerical model for reinforced rubber concrete frames by comparing the finite element results with the experimental results, providing a reliable theory for the study of progressive collapse of reinforced rubber concrete frames. Li et al. [6] proposed a method to evaluate the robustness of steel frames. The effects of different frame types and parameters on the progressive collapse and robustness of steel frames were analyzed through experiments and numerical simulations. Wang et al. [7] investigated the parameters of steel frames through experimental and numerical verification to analyze the continuous collapse behavior of steel frames with different connection methods when the columns are removed.

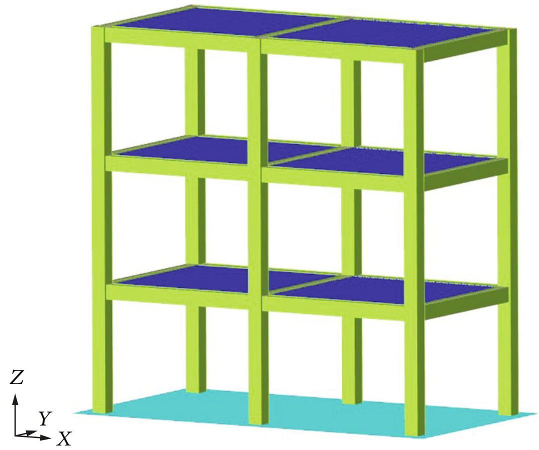
As an important element in the structure, the floor and infilled wall has also received extensive attention. Kim et al. [8] studied the influence of floor slab on the collapse of steel frame with missing columns through numerical analysis, and proposed a new model to help scholars calculate the energy of floor slab. Weng et al. [9] studied the load redistribution capacity of slabs under the failure of middle columns. Through experiments and finite element simulation, it was found that ignoring the constraints of surrounding slabs may reduce the load redistribution capacity of slabs. Yu et al. and Yu et al. [10, 11] found that the existence of infilled walls improved the collapse resistance of structures by establishing reinforced concrete infilled frame models with different heights of masonry infilled walls, different wall opening positions, areas, and layers. Shan et al. and Shan and Li [12, 13] designed bare frame, full-height infilled wall frame, and partially infilled wall steel frame. The research shows that the existence of infilled wall significantly improves the initial stiffness, but changes the failure mode of steel frame. The effect of fire on the progressive collapse of the steel frame structure was subsequently investigated by finite element software. Li et al., Shan et al., and Shan and Li [14–16] also discussed the influence of infilled walls on the anticollapse performance of reinforced concrete frames, and found that infilled walls were equivalent to compression struts during the collapse process, which increased the resistance and initial stiffness, but reduced the ductility of beams. After that, the interaction between infill walls and reinforced concrete frame members in the process of progressive collapse was studied experimentally, and two reinforced concrete frames with four spans and two floors were designed to simulate the absence of middle columns. It was found that infill walls can provide alternative load paths, thus improving the collapse resistance of concrete frames. Wang et al. [17] studied the performance of infilled walls in the process of collapse of precast concrete frames, and analyzed the influence of the opening position and size of infilled walls on the structure. In order to investigate the effect of floor slabs and infill walls on the resistance of three-dimensional reinforced concrete frame structures to progressive collapse, Feng et al. [18] validated the finite element model experimentally and showed that both floor slabs and infill walls significantly improved the resistance of the structure to progressive collapse.

Generally speaking, the alternative force transmission path method is a commonly used method to analyze the progressive collapse of structures, but this method cannot truly simulate the actual failure state of structures, especially for some abnormal loads or some large and tall buildings, and the requirements for experiments are extremely harsh, so researchers cannot accurately carry out relevant experimental research under limited conditions. By using the direct dynamic method of finite element software, the progressive collapse of building structures caused by explosion, impact, fire, or earthquake can be accurately and reliably simulated. By using the simplified analysis method, the causes of the progressive collapse of structures can be considered, and the calculation efficiency can be improved while ensuring the accuracy of the analysis results of the progressive collapse of structures. Li et al. [19] designed a layered shell element model based on the variation of structural dimensions at different locations of the tower. The results show that the established model can effectively simulate the collapse behavior of super-large cooling towers under wind load, and the internal force distribution process of the tower during the collapse process is analyzed, which is of great significance to the research of cooling towers. Sun et al. [20] put forward a new method and used Vulcan software to study the collapse behavior of steel structures with different designs in fire scenes. Jiang et al. [21] studied the influence of floor slab in different situations on the collapse of steel frame under blasting load by finite element software. Helmy et al. [22] designed according to UFC code, and studied the collapse of reinforced concrete frames with different components damaged by finite element software, and found that infill walls made an important contribution to the progressive collapse resistance of structures. Zhou [23], based on LS-DYNA software proposed a new simulation of concrete blasting work for updating the core algorithm of high-rise steel structure building. The results show that the similarity between the simulated structure and the actual work is improved, which provides a new analysis method for the demolition of high-rise steel structures. Sun and Cui [24] studied the collapse behavior of prefabricated structures after columns in different positions were damaged under multidimensional earthquake, and found that the collapse of structures after internal columns were damaged was the most serious. Qian et al. [25] investigated the effect of infill walls on the progressive collapse behavior of multistorey frames through finite element modelling and found that infill walls can improve the stiffness of the structure.

The contribution of nonstructural members to the collapse resistance of structures after failure of vertical members has generally not been considered in previous studies of progressive collapse of frame structures. However, while the effect of infill walls on the seismic performance of structures



(a)



(b)

Figure 1: Reinforced concrete frame structure. (a) With masonry infill walls. (b) Without masonry infill walls.

is generally recognized, not much research has been carried out on progressive collapse, and even less on progressive collapse of frame structures with infill walls under blast loads. Therefore, this paper uses the finite element software ANSYS/LS-DYNA to model a reinforced concrete frame with masonry infill walls, and apply blast loads to damage its central and side columns, respectively. The influence of the dosage and span number on the progressive collapse of the structure is considered, and compared with the bare reinforced concrete frame model, so as to provide a reference for the future research on the progressive collapse of this kind of structure.

2. Finite Element Model

The structure has two spans in the x-direction and one span in the Y-direction, with a column spacing of 3.8 m and a total of 3 floors for each floor height of 3 m. The cross-sectional size of the columns is 350 mm×350 mm with 6 longitudinal bars of 25 mm diameter. The beam cross-sectional size is 250 mm×350 mm with 6 longitudinal bars of 18 mm diameter. The hoop diameter is 10 mm and the spacing is 200 mm. The thickness of reinforced concrete floor slab is 100 mm, the floor reinforcement diameter is 10 mm and the spacing is 100 mm, and it has yield strength of 235 MPa. The reinforced concrete frame structure model and its design details are shown in Figures 1 and 2.

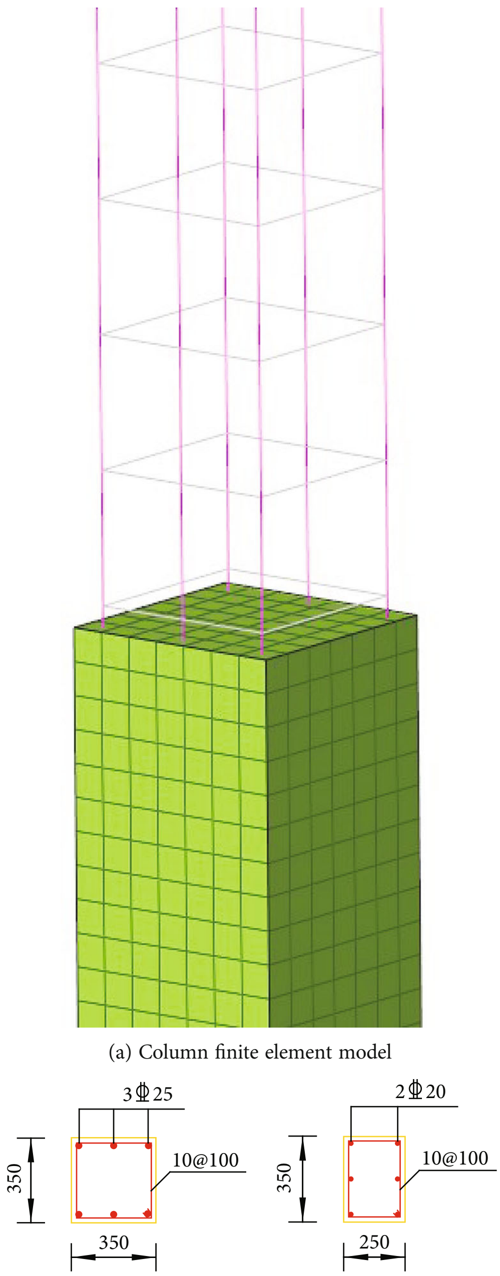
2.1. Material Model. The physical and mechanical parameters of the materials used in the example model are determined as shown in Table 1.

The concrete and infill wall units are simulated by SOLID164 solid unit, the reinforcement unit is simulated by BEAM161 beam unit, and the rigid floor is simulated by SHELL163 shell unit. The cell size is divided into 50 mm [26], and the mesh convergence analysis shows that further reduction of the mesh size will have less effect on the results, but the computation time will be greatly increased.

The concrete is simulated by *MAT_CONCRETE_DAMAGE_REL3 [27] material model. The model can effectively simulate the mechanical form of concrete materials under high strain rate and large deformation. The literature [28, 29] used this model to simulate concrete materials under explosive loading. The reinforcement is simulated by *MAT_PLASTIC_KINEMATIC elastic-plastic material model, which takes into account the strain rate effect of the material. The wall is simulated by *MAT-BRITTLE-DAMAGE material model. The interaction between the reinforced concrete elements and their interaction with the rigid ground was simulated using the *CONTACT_AUTO-MAATIC_SINGLE_SURFACE contact analysis model. For the bonding between the wall and the frame, the surface to surface contact algorithm (*CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK) is used to simulate the effect of mortar [27]. In accordance with the Chinese standard "Code for the Design of Masonry Structures" [30], the coefficient is taken as 0.7 for sliding between masonry and concrete. According to Yu's theoretical failure criterion, the contact parameter SFLS takes the shear strength of mortar and NFLS takes the tensile strength of mortar.

$$\left(\frac{|\sigma_n|}{\mathrm{NFLS}}\right)^2+\left(\frac{|\sigma_S|}{\mathrm{SFLS}}\right)^2\geq 1, \tag{1}$$

According to the research results of Shi et al., Xu and Lu, and Bibiana and Aráoz [26, 31, 32], the maximum principal strain critical value 0.1 and the maximum shear strain critical value 0.9 are selected as the basis for judging the erosion of beam-column concrete units. The minimum principal strain critical value of -0.01 is selected as the basis for judging the erosion of floor concrete units, and the failure compressive strain value and the failure tensile strain value are selected as the basis for judging the erosion of blocks.



(a) Column finite element model

(b) Column section

(c) Beam section

Figure 2: Design details for reinforced concrete frames.

2.2. Load. The load combination method of UFC4-023-03 specification [33] is used for vertical loads, considering the permanent load, and some live loads, and its load combination is

$$G = 1.2D' + 0.5\,L, \tag{2}$$

where D' and L represent the permanent load and live load of the structure, respectively. Vertical downward gravity is applied to the entire structure and a uniform load is applied to the floor slab. To apply gravity load to Frame 1 (with infill wall) and Frame 2 (without infill wall) as a whole by using the keyword *LOAD_BODY_Z. Selection of the floor face A and the upper face B of the beam as the surfaces to be loaded by using the keyword *SET_SEGMENT, and application of the uniform force to the floor face A by using *LOAD_SEGMENT_SET, and to the upper face B of the beam by converting the pressure of the infill wall into a uniform load on the beam for the bare frame.

The *LOAD_BLAST_EHANCED command [27] in LS-DYNA applies blast loads to the structure surface along the y-axis in the forward direction. The method is more convenient and automatic for handling blast loads by automatically converting TNT into a dynamic load on the unit surface to simulate blast impact effects based on the TNT equivalent and the distance from the target location.

3. Work Conditions

The influence of blasting load position, explosive charge, and span number of the structure on the collapse of concrete frame is considered. Frame 1: with infill wall frame; Frame 2: without infill wall frame.

3.1. Location of Explosives. The continuous collapse study of the concrete frame structure focused on the collapse behavior of the key columns after being damaged, so the blast location was chosen to be 3 m in front of the side and center columns, as shown in Figures 3 and 4.

3.2. Selection of Explosive Quantity. After applying the corresponding constant and live loads to the frame structure, the blast loads were applied to one side of the structure at t = 100 ms. This paper selects the distance from the middle column (or side column) 3 m before the location for the detonation point. After testing different amounts of charge, there was initial damage to the selected column and only slight initial damage to the column next to it, at which point the scaled distance ranged from $0.42\,\mathrm{m{\bullet}kg^{-1/3}}$ to $0.73\,\mathrm{m{\bullet}kg^{-1/3}}$. The collapse of structures at scaled distances D of $0.45\,\mathrm{m{\bullet}kg^{-1/3}}$, $0.48\,\mathrm{m{\bullet}kg^{-1/3}}$, and $0.51\,\mathrm{m{\bullet}kg^{-1/3}}$ are compared within this range.

4. Comparative Analysis of Collapse Results

4.1. Damage to the Bottom Middle Column. Figure 5 gives the collapse state at the 700 ms after the blast load is applied to both frames at a scaled distance $D = 0.45\,\mathrm{m{\bullet}kg^{-1/3}}$. As can be seen from the figures, both frames are subject to damage and failure due to blast loading on the central column, resulting in large deformation of the whole structure causing collapse damage. The overall collapse degree of reinforced concrete frame with infilled walls is obviously lower than that of reinforced concrete frame without infilled walls, and the bending shape of three-story beams has changed due to the support of infilled walls.

In order to compare and study the collapse of the structure and the collapse process when the bottom middle column fails, the maximum vertical displacement point after the bottom middle column fails is selected as the inspection point. In order to compare the initial impact of explosion

Table 1: Material physical parameters.

Material	Density/(kg•m^{-3})	Elastic modulus/GPa	Poisson ratio	Compressive strength/MPa
Concrete	2500	23	0.2	30
Steel reinforcement	7850	200	0.3	335,225
Masonry	2200	2.25	0.15	10

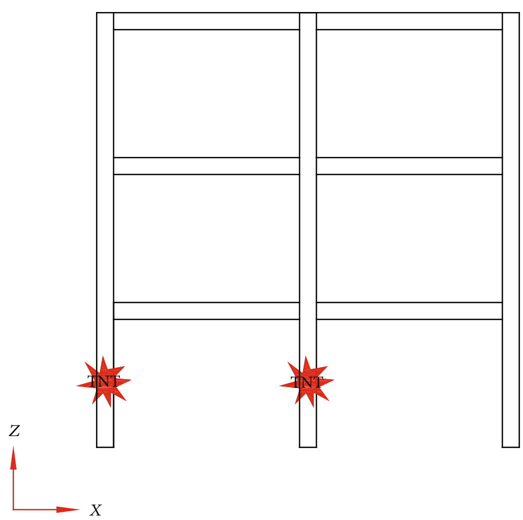


Figure 3: The position of explosives in X-Z plane.

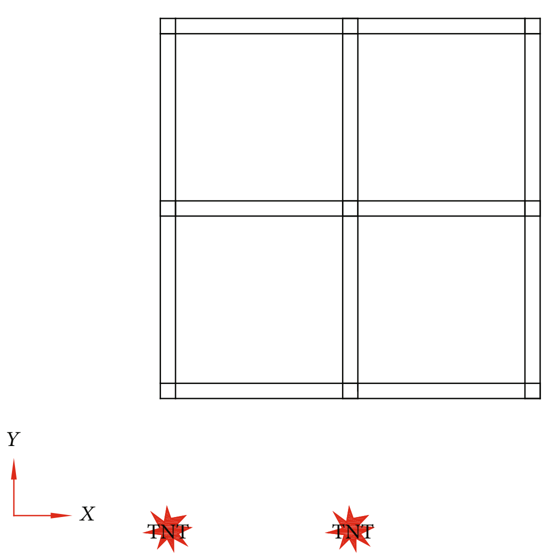


Figure 4: The position of explosives in X-Y plane.

load on other components except the damaged middle column, the dynamic characteristics of the top of the bottom middle column and the middle point of the second-floor middle column which are close to the middle column and greatly affected by the explosion load were investigated.

Figure 6 shows the time history curve of vertical displacement of the top of the three-story middle column under blasting loads with different scaled distance. The following can be seen from the figure: (1) the collapse of the structure is more severe when the proportional distance is smaller (the amount of explosives is larger). (2) In the early stages of structural damage, the frame collapses more slowly for a short period of time due to the presence of infill walls after being subjected to blast loads. When the bonding effect between the wall and the frame in the structure fails, the wall will fall off due to the dumping of the structure, and the collapse speed of the structure will be accelerated. Structures with infill walls collapse to a lesser extent in the same amount of time for different frame types at the same scaled distance.

Figure 7 gives the velocity time profile at the location of the top point of the column in the ground floor for different scaled distance of blasting loads. It can be seen from the graph that the velocity at this point increases rapidly for a short period of time and then decreases after the structure has been subjected to different scaled blast loads, and then increases again as the damaged area collapses. The speed of this point in Frame 1 is always lower than that of the corresponding position in Frame 2, so the vertical collapse displacement of the structure with infilled walls is smaller.

Figures 8 and 9 are the Y-direction velocity time history diagrams of the midpoint of the middle column on the second floor and the apex of the middle column on the bottom floor when the structure is subjected to blasting loads of different proportions, respectively. It can be seen from the figure: After the blasting load is applied, because the front of the structure receives the impact of explosives, the Y-direction velocity at this point increases in a very short time and then decreases to about 0, and then with the collapse of the structure, the velocity increases again. (2) The explosion load with different scaled distance affects the initial velocity peak, and the smaller the scaled distance, the greater the initial velocity peak. The speed of the damaged part of the structure with infilled walls in the Y-direction is smaller, and the displacement of the structure in the Y-direction is smaller, so it is not easy to collapse.

4.2. Damage to the Bottom Side Column. Figure 10 shows the collapse of two kinds of frame bottom side columns at 700 ms after the scaled distance $D = 0.45$ m•kg − 1/3 is applied. It can be seen from the figure that the collapse degree of Frame 1 is lower than that of Frame 2.

When the bottom column fails, the corresponding inspection points and units are as follows: the apex of the third-floor column, the apex of the bottom-floor column, and the midpoint of the second-floor column.

Figure 11 shows the time history curve of vertical displacement of the apex of the three-story side column under different scaled distance. The following can be seen from the figure: (1) when the scaled distance is smaller, the

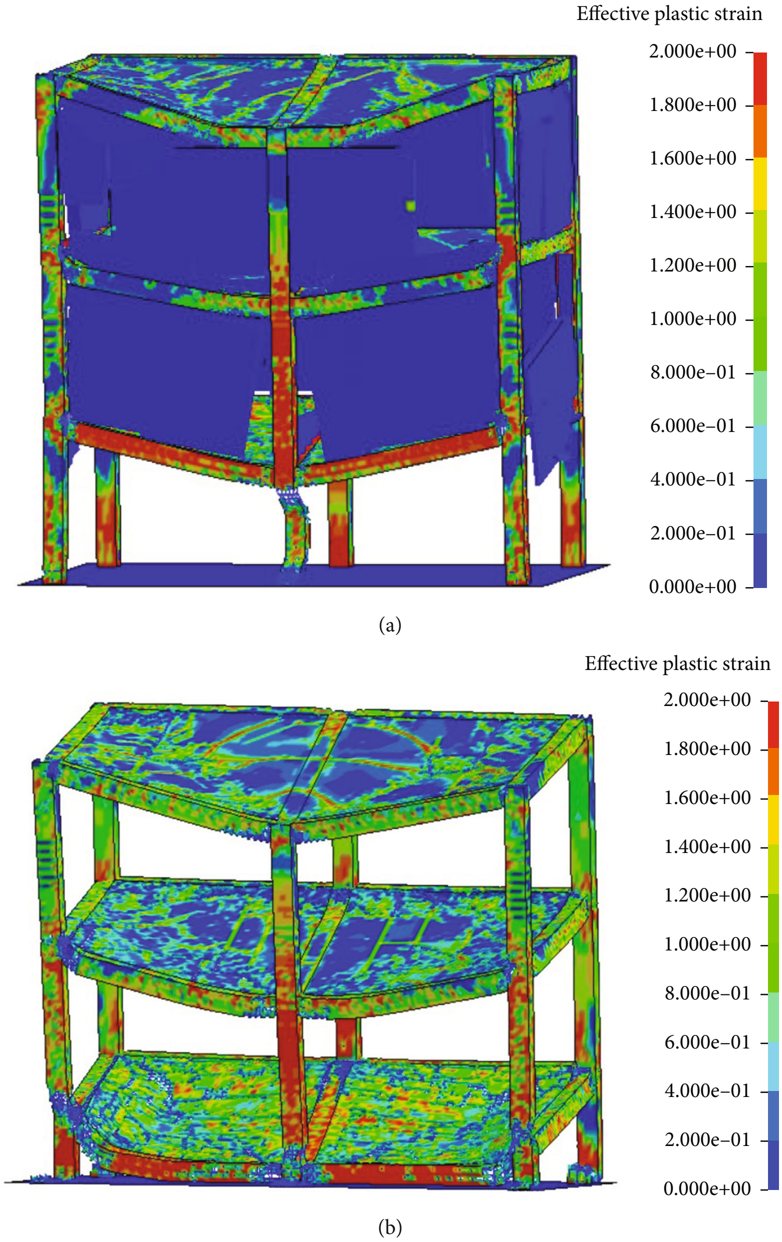


Figure 5: Collapse state of the frame when the middle column at ground floor is damaged. (a) Frame 1. (b) Frame 2.

progressive collapse time of the structure is shorter and the collapse speed is faster. (2) Under the same scaled distance of different frame types, the collapse speed of concrete frames without infilled walls is faster than that of concrete frames with infilled walls, and the structure with infilled wall is more difficult to collapse.

Figure 12 is the velocity time history curve of the apex position of the bottom side column under the condition of applying different scaled distance blasting loads. As can be seen from the figure, (1) after the structure is subjected to different proportions of blasting loads, the velocity at this point will increase rapidly in a short time, then decrease and then increase. (2) The velocity at this point in Frame 1 is significantly less than the velocity at the corresponding location in Frame 2, so the structure with infill walls collapses more slowly.

Figures 13 and 14 are the Y-direction velocity time-history diagrams of the midpoint of the second-story side column and the apex of the bottom-story side column when the structure is subjected to blasting loads with different scaled distance, respectively. After the blast load is applied, the Y-directional velocity at this point increases for a very short time and then decreases to about 0. The velocity then increases again as the structure collapses. At a scaled distance of 0.45 $m\bullet kg^{-1/3}$, the infill wall structure has a ground floor beam in contact with the ground at 750 ms and the Y-directional velocity is therefore reduced. The blast loads at different scaled distance affect their initial velocity peaks,

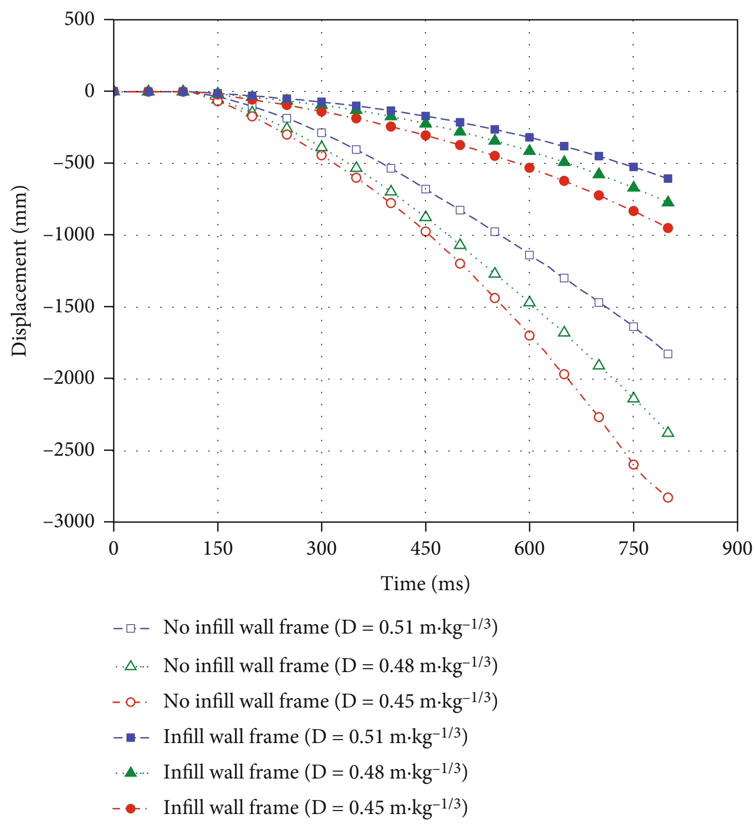


FIGURE 6: The z-directional displacement of the apex of the column in the third floor

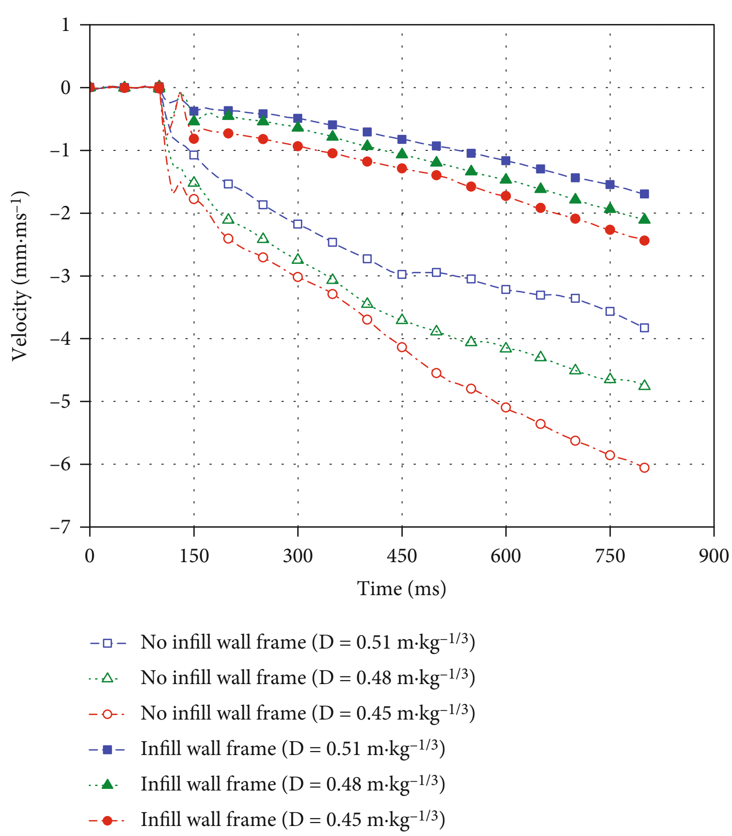


FIGURE 7: The z-directional velocity at the apex of the bottom middle column

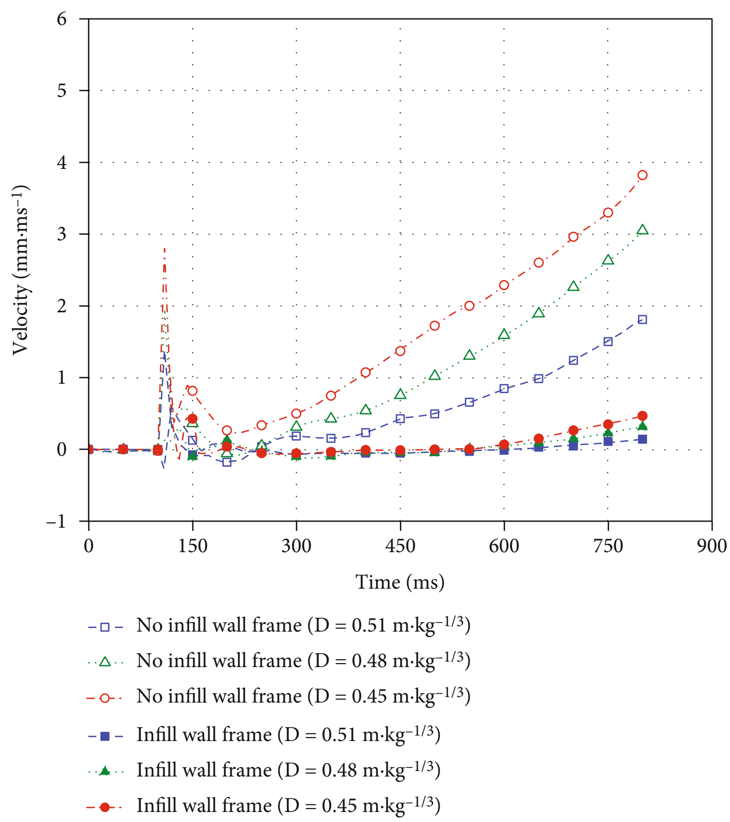


FIGURE 8: The Y-direction velocity of column midpoint in the second floor.

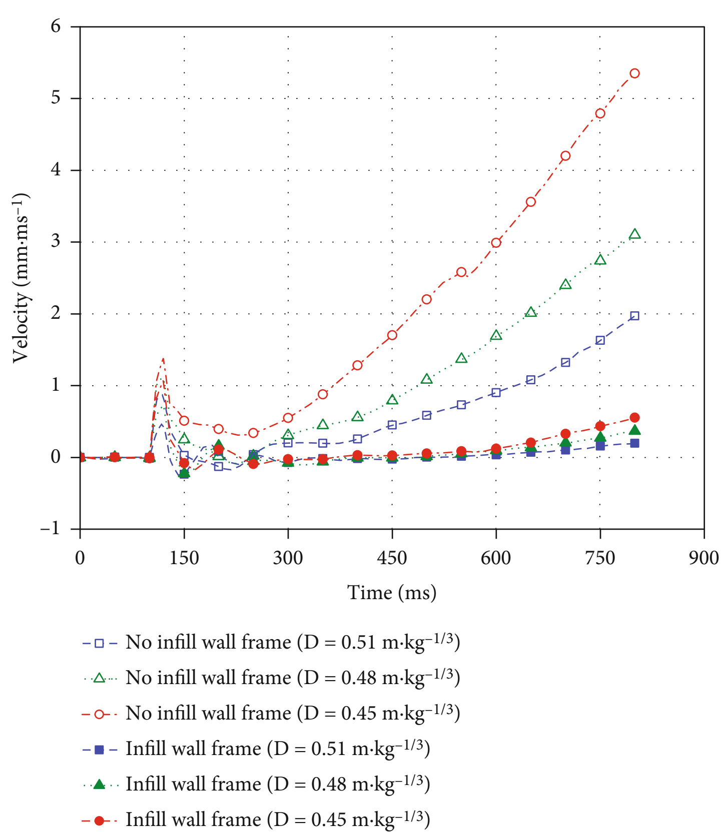
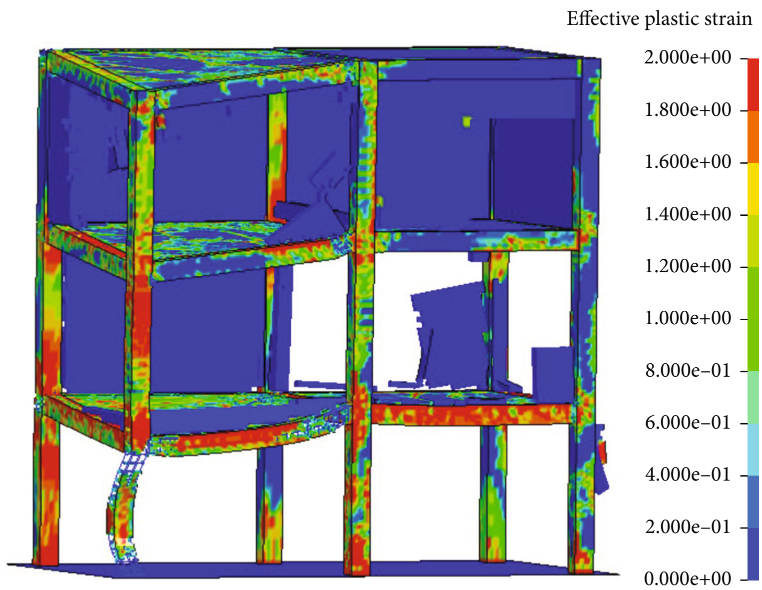
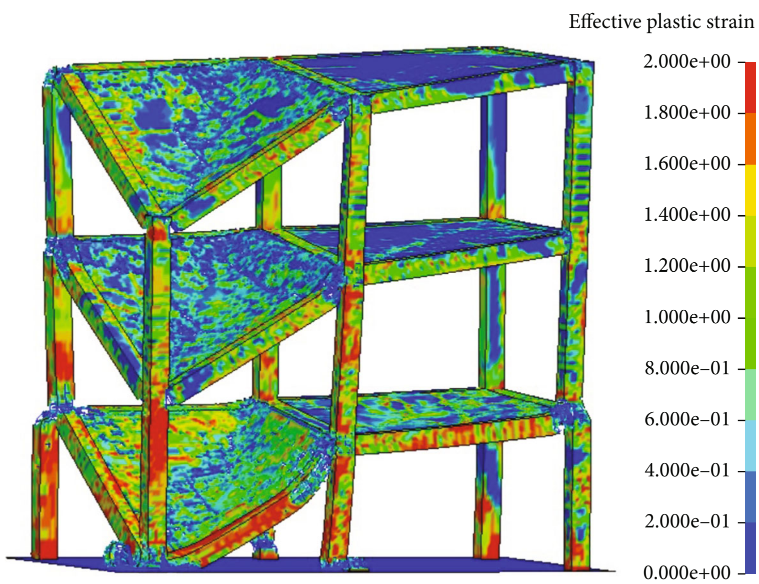


FIGURE 9: The Y-direction velocity of the apex of the bottom column,



(a)



(b)

Figure 10: Collapse state of the frame when the side column at ground floor is damaged. (a) Frame 1. (b) Frame 2.

with smaller scaled distance resulting in larger initial velocity peaks. Under the blasting load of the same scaled distance, the velocity of two points on the structure with infilled walls is always lower than that of the corresponding points on the frame without infilled walls, so the structure with infilled walls has a lower degree of collapse in the same time.

4.3. Effect of Span Number on Structural Collapse. In order to investigate the effect of the number of spans on the collapse performance of concrete frames with masonry infill walls, three-story two-span, three-story three-span, three-story four-span structural models are established, which have two spans, three spans and four spans in the X direction, respectively, and one span in the Y-direction, as shown in Figure 15.

The blast load of scaled distance $D = 0.45\,\mathrm{m{\bullet}kg^{-1/3}}$ is applied to the side columns at 100 ms for structures of different spans. The z-directional displacements at the apex of the three-storey side columns and the midpoint of the two-storey side columns at 700 ms after damage are shown in Figures 16 and 17, respectively. At 700 ms after damage, the top displacement of the third-floor side column of the two spans, three spans, and four spans structures with infilled walls is 502 mm, 547 mm, and 665 mm, respectively, and the top displacement of the third floor side column of the two spans, three spans, and four spans structures without infilled walls is 2780 mm, 3020 mm, and 3082 mm, respectively. It can be seen that as the number of spans increases, the vertical displacement of the structure at the point of damage increases and the structure is more prone to collapse.

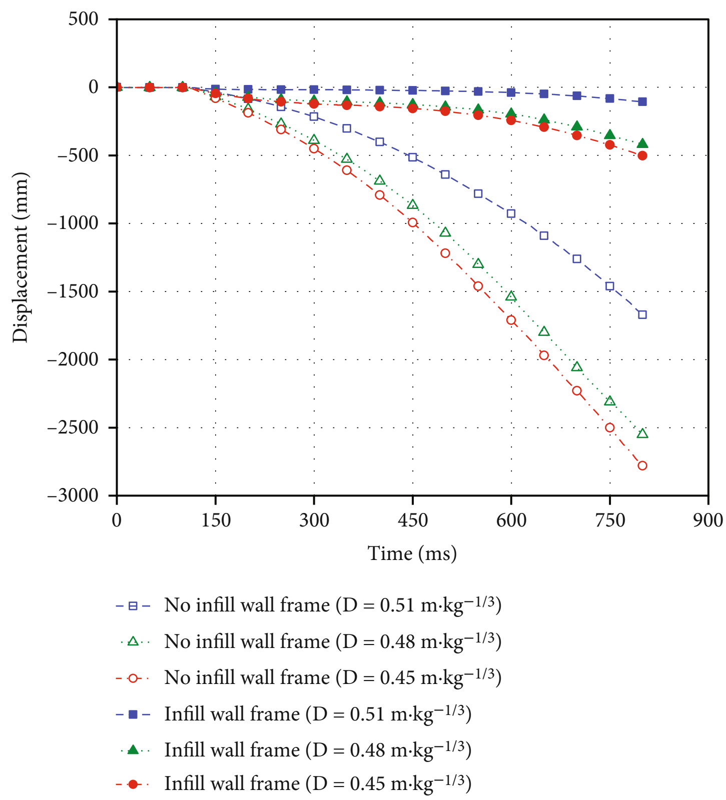


Figure 11: The z-directional displacement of the apex of the column on the third floor.

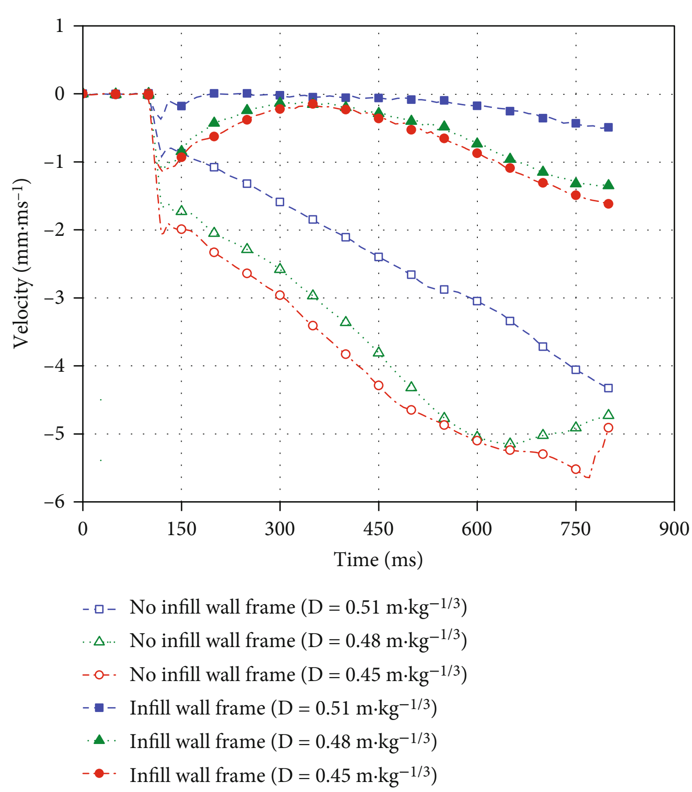


Figure 12: The z-direction velocity of the apex of the bottom column.

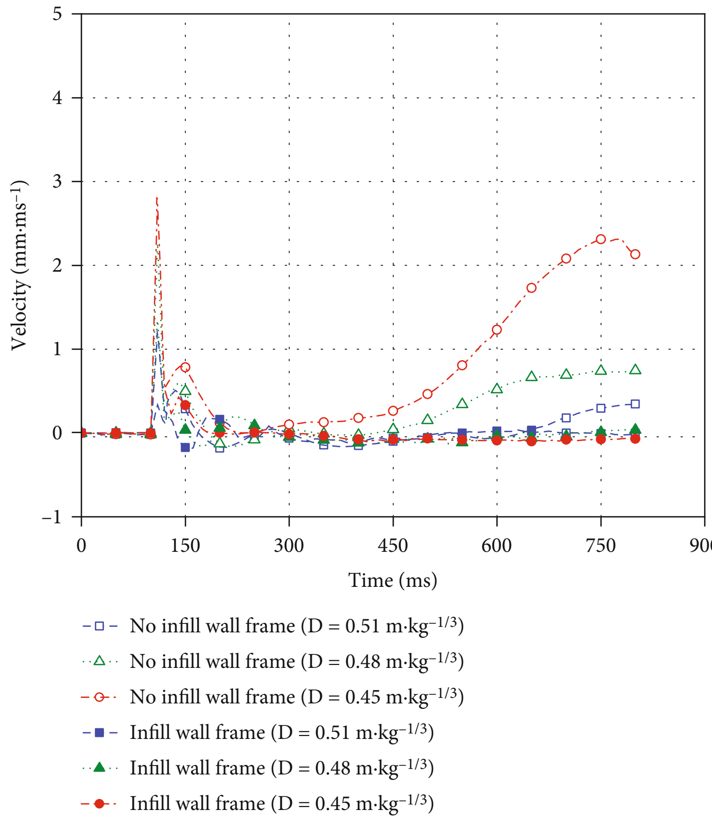


FIGURE 13: The Y-directional velocity at the midpoint of the second story side column.

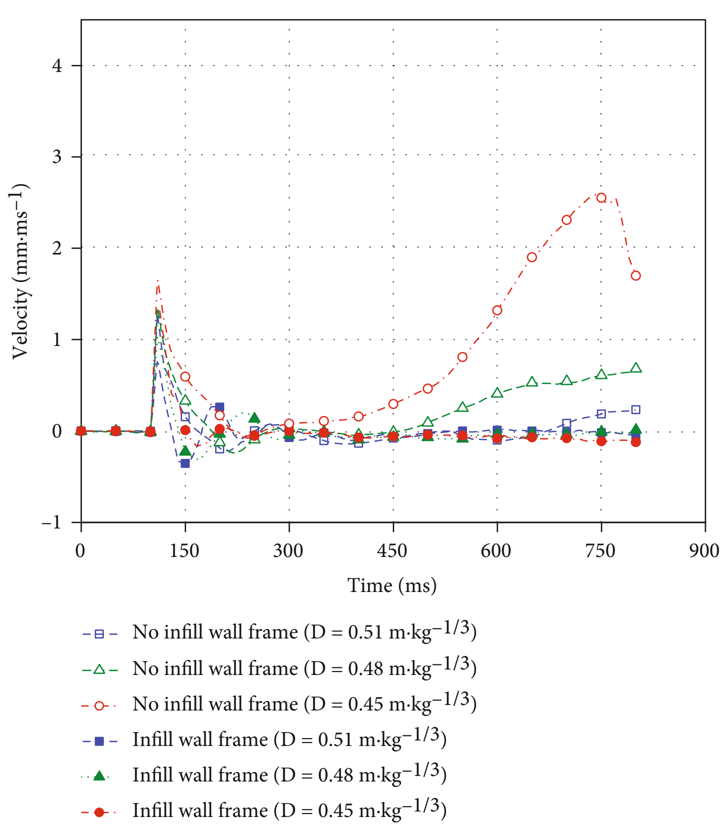
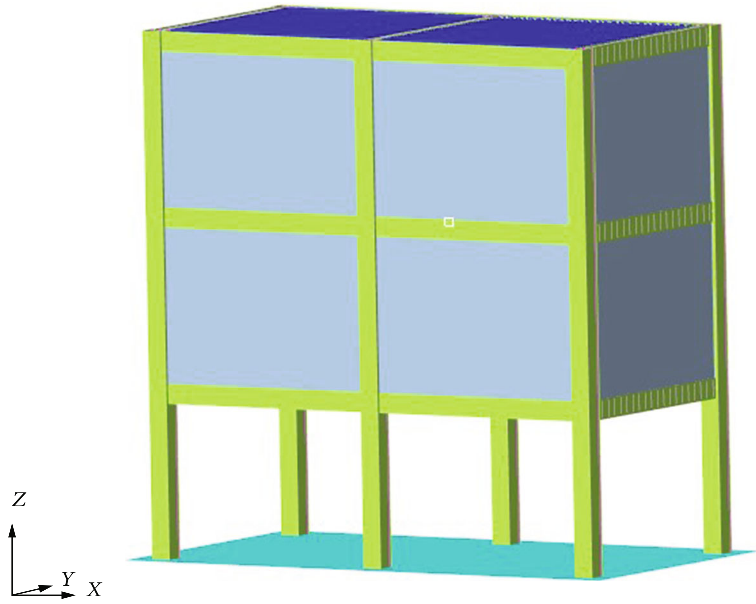
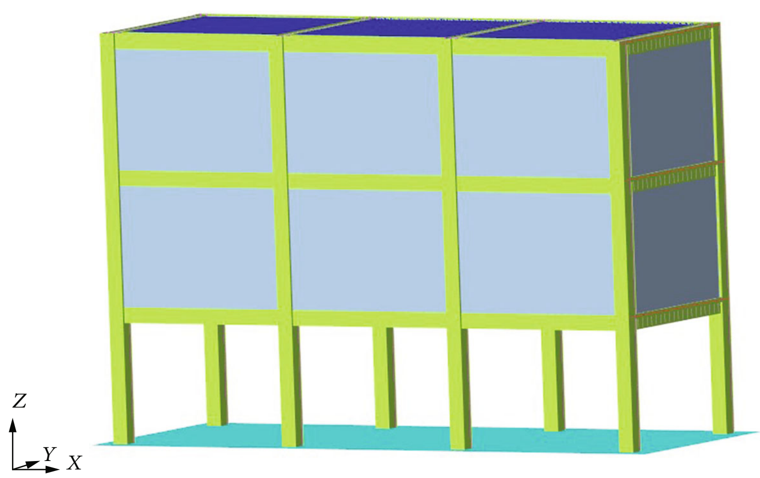


FIGURE 14: The Y-directional velocity at the apex of the bottom side column.



(a)



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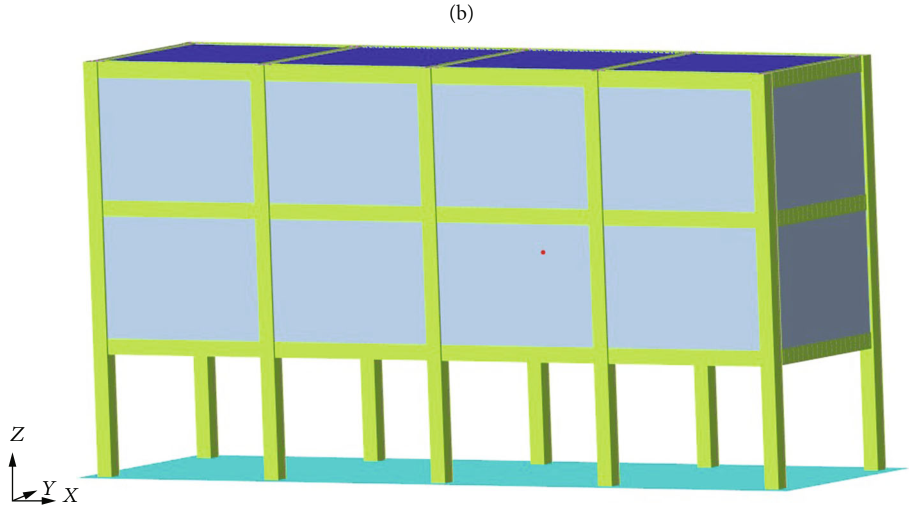

(c)

FIGURE 15: Reinforced concrete frame model. (a) Two spans. (b) Three spans. (c) Four spans.

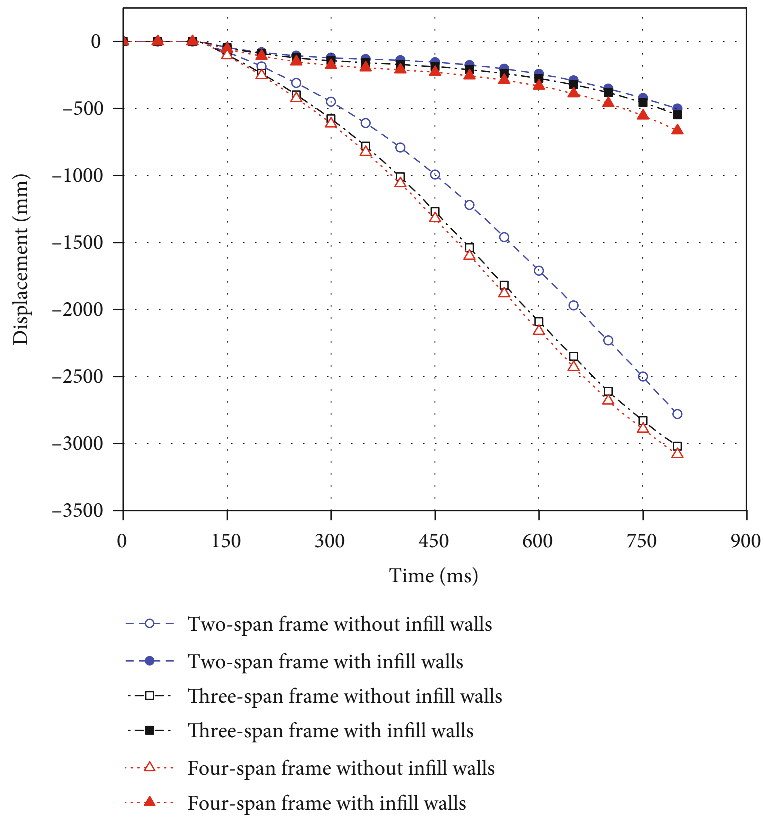

FIGURE 16: The z-directional displacement at the apex of the three-story side column after damage.

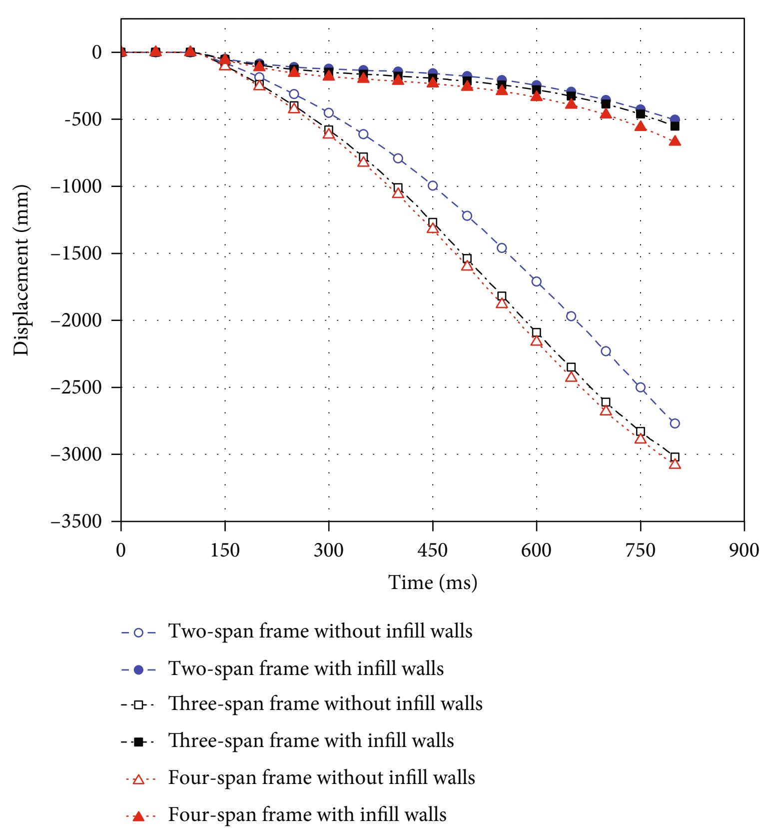

FIGURE 17: The z-directional displacement at the midpoint of the second-story side column after damage.

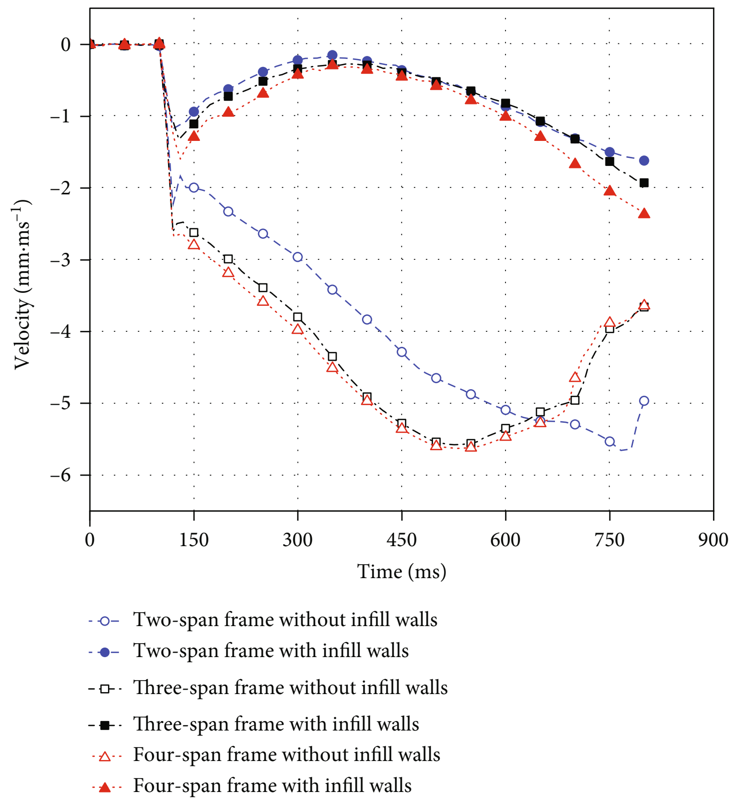

Figure 18: The z-direction velocity at the midpoint of the second floor side column.

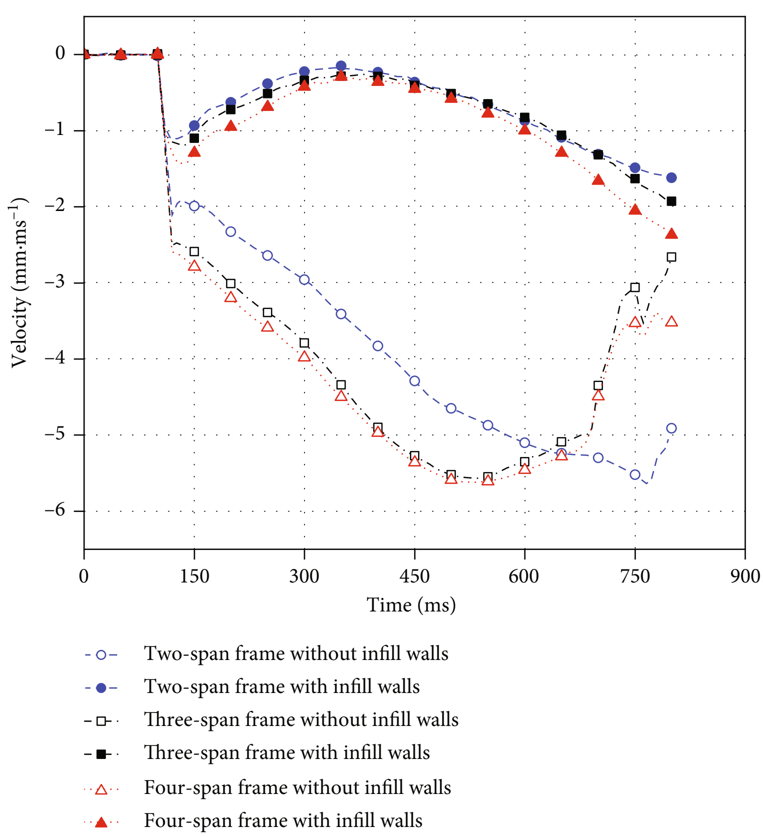

Figure 19: The z-direction velocity at the apex of the bottom side column.

Figures 18 and 19 show the z-directional velocity at the midpoint of the second-floor side columns and the z-directional velocity at the apex of the bottom floor side columns, respectively, after damage. It can be seen from the figures that for different span numbers, the structure collapses faster as the number of spans increases; the structure with infill walls collapses to a lesser extent in the same time compared to the structure without infill walls.

5. Results and Discussion

In this paper, the continuous collapse process of reinforced concrete frame structures with masonry infill walls under blast loading is investigated using a nonlinear dynamic method. By comparing with structures without infill walls, it is found that infill walls have a nonnegligible role in the initial stage of structural collapse and have positive implications for the collapse resistance of the structure. The main conclusions are as follows:

(1) By analyzing the collapse of frame structures under different scaled distance blast loads, the higher the initial charge the greater the damage to the structural columns and the faster the collapse of the structure

(2) The results of each working condition analysis show that compared with the frame structure without infilled walls, the collapse degree of the frame structure with infilled walls is obviously lower in the same time. The infill walls provide support to the structure in the early stages of collapse, acting as a new force transfer path in addition to the beams and columns, slowing down the collapse of the structure in the early stages. Therefore, the infill wall is a factor that cannot be ignored in the research of the continuous collapse resistance of structures

(3) With the increase of the span number of the frame structure, the vertical displacement of the damaged structure increases, and the collapse speed of the structural members accelerates. The structure with few spans has better resistance to continuous collapse

(4) During the collapse of the structure, the walls fall off due to the failure of the bond between the elements as the structure topples over. After the infilled wall loses its supporting function to the structure, the collapse of the structure with infilled wall tends to the collapse of the structure without infilled wall. It is suggested to use mortar with better bonding property to ensure the bonding ability between concrete structure and blocks, so as to improve the anticollapse ability of the structure

Data Availability

The data used to support the study are available from the corresponding authors upon request.

Conflicts of Interest

The author declares that the copyright of this paper belongs to the first author at present, and there is no conflict of interest in the publication of this paper.

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