Numerical Analysis on Collapse of Steel Frame Considering Floors under Blast Load

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Abstract. Based on the fluid-solid coupling method, the ANSYS/LS-DYNA software is used to simulate the collapse of a three-story steel frame considering floors under blast load, and analysis of dynamic response and failure mode of the steel frame is carried out under the influence of factors such as floors, position of opening, opening rate and opening floors. The results show that under blast load, the existence of floors adversely affects the collapse of the steel frame, and it is more likely to lead to the collapse of the steel frame that position of opening is directly above the detonation point, opening rate is smaller and opening floors are at bottom. The continuous opening of floors has no obvious influence on the collapse of the steel frame under blast load.

1. Introduction
Steel frame is one of the structural forms widely used in engineering construction. Domestic and foreign scholars have done some research on the collapse of the steel frame under blast load[1-3], but there are few studies on the impact of floors. In this paper, the ANSYS/LS-DYNA software is used to establish a three-story steel frame finite element model and the collapse of the steel frame affected by the factors of floors is simulated[4]. Analysis of dynamic response and failure mode is carried out.

2. Finite element model

2.1. Parameters of model
The steel frame has a plane size of 18m×18m, three spans in both horizontal and vertical directions, the column spacing of 6m, the floor height of 4m and three floors. The column section is HM350mm×250mm×9mm×14mm and the beam section is HM300mm×200mm×8mm×12mm. The grade of steel is Q345. The thickness of floors is 100mm and the grade of concrete is C30.

BEAM161 beam element is selected for steel columns and beams, and SHELL163 shell element is selected for concrete floors. *MAT_PLASTIC_KINEMATIC plastic follow-up hardening model is selected for the material of steel and concrete.

SOLID164 solid element is selected for high explosives and *MAT_HIGH_EXPLOSIVE_BURN model is selected for the material of high explosives. This model is usually used in conjunction with *EOS_JWL equation of state. The reference[5] gives the equation as:
In the equation (1), \( p \) is the detonation pressure and the unit is Pa; \( E \) is the internal energy density per unit initial volume, which is \( 7 \times 10^9 \) J·m\(^{-3} \); \( V \) is the initial relative volume, which is 1; \( A=3.71 \times 10^{11} \) Pa, \( B=3.23 \times 10^{11} \) Pa, \( R_1 = 4.15 \), \( R_2 = 0.9 \) and \( \omega = 0.3 \) are all parameters related to the properties of high explosives.

SOLID164 solid element is selected for air and *MAT_NULL model is selected for the material of air. The model combines with the linear polynomial state equation *EOS_LINEAR_POLYNOMIAL to describe the pressure expression, and the reference[5] gives the equation as:

\[
p(t) = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + \left( C_4 + C_5 \mu + C_6 \mu^2 \right) E
\]

In the equation (2), \( p \) is the pressure and the unit is Pa; \( \mu \) is the dynamic viscosity coefficient, which is 0; \( E \) is the initial internal energy per unit reference specific volume, which is \( 2.53 \times 10^5 \) J·m\(^{-3} \); \( C_0 = -1 \times 10^5 \) Pa, \( C_1 = 0 \) Pa, \( C_2 = 0 \) Pa, \( C_3 = 0 \) Pa, \( C_4 = 0.4 \) Pa, \( C_5 = 0.4 \) Pa and \( C_6 = 0 \) Pa are all parameters related to properties of air.

SHELL163 shell element is selected for rigid ground and *MAT_RIGID model is selected for the material of rigid ground. The rigid model can be used to improve the computational efficiency and reduce the computational amount of contact and penetration inspection during the simulation.

2.2. Fluid-solid coupling
In the finite element model, explosives-air element surrounds all the steel frame structures (excluding rigid ground) element. The elements of steel columns and beams, concrete floors and rigid ground are computed by using Lagrange algorithm[6] and the element of explosives-air is computed by using ALE algorithm[6]. In order to simulate the damage of the steel frame under blast load, the computation of fluid-solid coupling is implemented by the keyword *CONSTRAINED_LAGRANGE_IN_SOLID. This method can avoid errors of computation caused by excessive mesh distortion.

3. Factors of floors
The factors such as floors, position of opening, opening rate and opening floors are considered, which affect the collapse of the steel frame under blast load.

3.1. Floors
The finite element models of steel frame with and without floors are simulated. The explosion equivalent is 44.28kg and the detonation point is at the midpoint of the steel frame’s edge on the bottom floor and at a distance of 1m from the ground, as shown in figure 1.

3.2. Position of opening
The position of opening is only on the bottom floor. The explosion equivalent is 13.12kg and the detonation point is at the midpoint of the steel frame’s corner on the bottom floor and at a distance of
1m from the ground. The relative position of opening and detonation point should be considered specially and the following models are built for simulation:

1) The detonation point is at corner: the position of opening is at corner, at edge and in the middle, as shown in figure 2 and figure 3.

2) The detonation point is at edge: the position of opening is at corner, at edge and in the middle.

3) The detonation point is in the middle: the position of opening is at corner, at edge and in the middle.

3.3. Opening rate
The position of opening is at corner of steel frame on the bottom floor for simulation. The opening rate of floors are: 11.11%, 25% and 44.44%. The explosion equivalent is 13.12kg and the detonation point is at the midpoint of the steel frame’s corner on the bottom floor and at a distance of 1m from the ground.

3.4. Opening floors
The position of opening is at edge of the steel frame for simulation. The opening floors are: bottom opening; middle opening; top opening; bottom and middle opening; bottom and top opening; middle and top opening; bottom, middle and top opening. The explosion equivalent is 13.12kg and the detonation point is at the midpoint of the steel frame’s edge on the bottom floor and at a distance of 1m from the ground.

4. Analysis of results

4.1. Floors

![Figure 4: The displacement-time curves with and without floors.](image)

The average displacement-time in the y-axis direction of the top beam-column joints of the steel frame with and without floors is in shown in figure 4. The displacements increase firstly, and the maximum displacements are 0.05857m at 0.16598s and 0.0167m at 0.01499s in the positive direction of the y-axis. Subsequently, in the case of full floors, the displacement develops rapidly and the y-axis negative maximum displacement of 3.19591m is achieved at 2.58989s. The steel frame collapses rapidly at this stage. In the case of no floors, the displacement develops slightly and the y-axis negative maximum displacement of 0.10479m is achieved at 0.14898s. Then it oscillates below 0m. The steel frame oscillates up and down but does not collapse with a certain downward deformation.

By studying the effective stress and plastic strain of columns’ top elements of the steel frame with and without floors, we learn that within 0s~0.003s after the explosion occurs (after 0.003s, due to the failure of some components, the stress and strain values are zero), the effective stress of specified elements of the steel frame with floors is larger than that without floors, and the effective plastic strain of specified elements of the steel frame with floors is smaller than that without floors. In summary, under blast load, the existence of floors adversely affects the stress of the steel frame. The pulling effect of the floors inhibits the damage and deformation of the beams, columns and joints.
to an extent, but due to the self-weight of the structure, remaining steel columns are subjected to excessive load and deform until they are invalid. Therefore, the existence of floors is accompanied by a large self-weight, which is very detrimental to the collapse of the steel frame under blast load.

4.2. Position of opening

![Figure 5. The displacement-time curves of corner detonation.](image1)

![Figure 6. The displacement-time curves of edge detonation.](image2)

![Figure 7. The displacement-time curves of middle detonation.](image3)

![Figure 8. The displacement-time curves of openings directly above the detonation point.](image4)

By studying average displacement-time curves in the y-axis direction of the top beam-column joints of the steel frame from figure 5 to figure 8, the information is summarized that in the cases of corner opening with corner detonation and edge opening with edge detonation, the displacements develop rapidly toward the negative direction of the y-axis and the steel frames collapse at the stage. The displacements of other cases oscillate near 0m and the steel frames all oscillate up and down without collapse. Specifically, because of the symmetry of numerical simulation, the steel frame of middle opening with middle detonation does not collapse.
In summary, when the position of opening is not directly above the detonation point, due to the weak transitivity, the propagation of blast wave is limited by floors. Otherwise, blast wave will spread rapidly to upper parts of the steel frame with little weakened. The partial opening has little effect on the self-weight of the structure. Remaining steel columns are subjected to excessive load and deform until they are invalid, and the steel frame collapses. Therefore, the position of opening which is directly above the detonation point can be regarded as the most disadvantageous opening position of the steel frame.

4.3. Opening rate

![Graph 1](image1)

Figure 9. The displacement-time curves with different opening rates of floors.

The average displacements in the y-axis direction of the top beam-column joints of the steel frame increase firstly in figure 9 when the opening rate of floors are 11.11%, 25% and 44.44%, and y-axis positive maximum displacements of 0.01559m, 0.00943m and 0.0156m are achieved at 0.0719s, 0.048s and 0.09394s. Subsequently, the displacement of the 11.11% opening rate rapidly and the maximum displacement is 7.46406m at 2.57094s in the negative direction of the y-axis. The steel frame collapses rapidly at this stage. The displacement of the 25% opening rate develops slowly and the maximum displacement is 1.14927m at the end of the computation time of 3s in the negative direction of the y-axis, and it has a tendency to continue to develop. It can be inferred that the steel frame deforms downward slowly until it collapses. The displacement of the 44.44% opening rate oscillates near 0m. At this stage, and the steel frame oscillates up and down without collapse.

In summary, the large opening rate of floors reduces the self-weight of the structure to an extent and the steel frame is not easy to collapse. For the opening rate, the self-weight of floors plays a leading role in the collapse of the steel frame under blast load. Therefore, the smaller the opening rate, the larger the self-weight of the structure, remaining steel columns are more subjected to excessive load and deform until they are invalid, and the steel frame collapses more seriously under blast wave.

4.4. Opening floors

![Graph 2](image2)

Figure 10. The displacement-time curves with different opening floors.
The average displacements in the y-axis direction of the top beam-column joints of the steel frame increase firstly in figure 10 in the seven cases of opening floors. The displacements are larger in the cases of bottom and middle opening and bottom, middle and top opening, and the maximum displacements are 0.73315m at 0.44199s and 0.86336m at 0.43398s in the positive direction of the y-axis. Subsequently, in the cases of middle opening, top opening and middle and top opening, the displacements oscillate near 0m, and the steel frames oscillate up and down without collapse. In the cases of bottom opening, bottom and middle opening, bottom and top opening and bottom, middle and top opening, the displacements develop rapidly and the y-axis negative maximum displacements of 6.77227m, 7.52655m, 7.00033m and 6.02417m are achieved at 3s, 2.929s, 3s and 3s. The steel frames collapse rapidly at this stage.

In summary, when opening floors are not at bottom, the propagation of the blast wave is limited. The opening of floors reduces the self-weight of the structure and the steel frame is not easy to collapse. The opening of bottom floors is conducive to the propagation of blast wave, which is more likely to cause the collapse of the steel frame. Because of the locality of blast wave, the continuous opening of floors has no obvious influence on the collapse of the steel frame under blast load.

5. Conclusion
1) Considering whether there are floors or not, under blast load, the steel frame with floors is more likely to collapse than that without floors and the existence of floors adversely affects the collapse of the steel frame.
2) Considering the relative position of opening and detonation point, under blast load, when the opening position of floors is directly above the detonation point, the collapse of the steel frame is more serious, and this situation can be regarded most disadvantageous.
3) Considering the opening rate, under blast load, when the position of opening is above the detonation point, the smaller the opening rate of floors, the more serious the collapse of the steel frame.
4) Considering the opening floors, under blast load, it is more likely to cause the collapse of the steel frame that opening floors are at bottom. The continuous opening of floors has no obvious influence on the collapse of the steel frame.

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