Study on the Performance of Box-Shaped Steel Columns under Blast Loading

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Abstract. To study on the performance of box-shaped steel columns with fixed end constraints under blast loading, the dynamic response of box-shaped steel columns under different loading conditions is analyzed through ANSYS/LS-DYNA software. Moreover, the change process of stress, deformation, as well as failure model is studied. Meanwhile, parameter analysis method is used to assess the influence of blast loading and width-thickness ratio on the failure model and dynamic response. The results show that local deformation is a significant feature of thin walled box steel columns under blast loading. With the increase of width-thickness ratio, the column lateral displacement is increased under blast loading. Reasonable design of influence parameters can ensure that box shaped steel columns have better blast-resistant ability.

1. Introduction
As an important load-bearing component of the building structure, steel columns play an extremely important role. Magallanes[1] studied the dynamic response, failure mode of concrete columns and steel columns through experiments. The finite element simulation is used to verify the experimental model, which provides a basis for the study of the blast resistance performance of the column. Chen and Liew[2][3] studied the dynamic response and failure mode of steel columns with different column ends under blast loading by numerical simulation. The ultimate blast loading at the time of steel column failure is obtained. Zhang Xiuhua[4-6] simulated the failure modes and dynamic response of steel frame columns and high-strength H-shaped steel columns under blast loading by finite element analysis. Li Guoqiang and Sun Jianyun[7][8] studied the dynamic response and failure modes of reinforced concrete columns, I-shaped steel columns and steel frame columns under blast loading through experiments and numerical simulations. The influence of blast load form, slenderness ratio and axial compression ratio on the dynamic response of various components are analyzed.

Although the performance of H-shaped steel columns, C-shaped steel columns and I-shaped steel columns under blast loading has been studied, but for thin-walled structures, such as box-shaped steel columns, the performance under blast loading is still scarce. It is of engineering significance and theoretical value to study blast resistance performance of box-shaped steel columns under blast loading[9].

2. Model and failure mode
2.1. Model overview
The steel column is made of Q345 steel with both ends fixed. Among them, the section width of the column is 200 mm, the height of the column is 200 mm, the thickness of the section is 12 mm for \( t_w \), 12 mm for \( t_f \), and the length of the column is 3000 mm. The section diagram and the overall loading diagram are shown in figure 1-2, respectively.

The SOLID164 entity unit type is selected to simulation. The model mesh has a dimension of 3 mm in the thickness direction of the section and a dimension of 100 mm in the longitudinal direction of the steel column (Figure 3); A triangular blast load is applied to the box-shaped steel column, the expression is:

\[
P(t) = P \left(1 - \frac{t}{t_0}\right)
\]

2.2. Loading conditions and failure mode
The stress cloud diagram of the deformation and failure process of box steel columns under blast loading (Table 1) is shown in Figure 4:

| Case | Section size (mm×mm×mm×mm) | Loading cases (MPa×ms) |
|------|-----------------------------|------------------------|
| ①   | 400×400×12×12               | 20×1                   |
| ②   | 200×200×9×9                 | 27×1                   |
| ③   | 150×150×12×12               | 2×10                   |

Figure 1. Box section Figure 2. Monolithic construction

Figure 3. Finite element model of box steel column (Rigid joints at both ends)

Figure 4. Stress cloud diagram under cases ①, ②, ③
3. Parameter analysis

To study the influence of parameters such as blast loading and width-thickness ratio, the dynamic response and failure mode of box-shaped steel columns on parameter analysis method is used.

3.1. Blast loading

The effects of blast loading on the dynamic response and failure mode of box-shaped steel columns are studied by considering three key variables: loading impulse, over pressure peak and duration:

As shown in Figure 5, in CASE 1, 2, and 3, the loading impulse is 30 MPa•ms, and the over pressure peak is 3 MPa, 6 MPa, and 10 MPa, and the duration is 10 ms, 5 ms, and 3 ms, respectively. Under different load conditions, combined with the mid-point displacement time-history curve analysis of the incident surface, it can be obtained that when the loading impulse is constant, the horizontal displacement and deformation of the column increase with the increase of over pressure. When the over pressure peak is small, it only causes local deformation and local destruction of the column.

As shown in Figure 6, in CASE 1, 2, and 3, the duration is 10 ms at the same time, the load impulses are 20 MPa•ms, 30 MPa•ms and 40 MPa•ms, and the over pressure peak is 2 MPa, 3 MPa and 4 MPa, respectively. Under different load conditions, combined with the mid-point displacement time-history curve, it can be obtained that the horizontal displacement and deformation of the column increase with the increase of over pressure when the duration is constant. When the impulse and duration are both large, it only causes the overall bending failure of the column.

As shown in Figure 7, in CASE 1, 2, and 3, the over pressure peak was taken at 3 MPa, and the load impulses were 15 MPa•ms, 30 MPa•ms and 45 MPa•ms, and the duration was 5 ms, 10 ms and 15 ms, respectively. Under different loading conditions, combined with the mid-point displacement time-history curve, it can be obtained that when the over pressure is constant, the horizontal displacement and deformation of the column are larger as the duration increases. When the load impulse and the duration are both large, it can be approximated as a quasi-static load, and overall bending deformation occurs.

3.2. Width-thickness ratio

The width-to-thickness ratio of the box-shaped steel column is analyzed to understand its influence on the dynamic response.
3.2.1. Changing the section thickness.

Table 2. Loading conditions

| Case | \( t_w \) \( t_t \) (mm) | Width-thickness ratio | Loading cases (MPa×ms) |
|------|-----------------------------|-----------------------|------------------------|
| I    | 6.0                         | 33.3                  | 27×1                   |
| II   | 9.0                         | 22.2                  | 27×1                   |
| III  | 12.0                        | 16.7                  | 27×1                   |
| IV   | 15.0                        | 13.3                  | 27×1                   |

Figure 8. mid-point displacement time history

Keep the section width and loading unchanged; the section width \( b, h \) should be taken at 200mm, the over pressure is 9MPa, and the duration is 3ms. The section thickness should be changed to adjust the width-to-thickness ratio of the steel column (Table 2). The time history of the midpoint displacement (Figure 8) shows that as the ratio of width-to-thickness increases, the horizontal displacement and deformation increase in the column.

3.2.2. Changing the section width.

Table 3. Loading conditions

| Case | \( b \) \( h \) (mm) | Width-thickness ratio | Over pressure peak (MPa) |
|------|------------------------|-----------------------|--------------------------|
| I    | 250.0                  | 20.8                  | 14.4                     |
| II   | 300.0                  | 25.0                  | 12.0                     |
| III  | 350.0                  | 29.2                  | 10.3                     |
| IV   | 400.0                  | 33.3                  | 9.0                      |

Figure 9. mid-point displacement time history

Keep the thickness of the section and loading constant. The section thickness \( t_w \) and \( t_t \) are taken as 12mm, and the duration is 3ms. Change the section width to adjust the width to thickness ratio of the steel column (Table 3). It can be seen from the time-history of the midpoint displacement(Figure 9) that as the width-thickness ratio increases, the horizontal displacement and deformation in the column increase.

4. Conclusion

In this paper, the performance of box-shaped steel columns with fixed ends under blast loading is studied. The dynamic performance and failure modes of box-shaped steel columns under different loading conditions are analyzed through finite element software. And the blast loading, width-thickness ratio, etc. are studied by parameter analysis. The influence of parameter factors on its failure mode and dynamic response is gained. The main conclusions are as follows:

(1) Local deformation is a remarkable feature of the reaction of thin-walled box-shaped steel columns subjected to blast loading. When the over pressure peak is large and the duration is small, the local deformation is more obvious. As the over pressure peak decreases and the duration increases, the box-shaped steel column changes to a bending failure mode.
(2) As the width-to-thickness ratio increases, the displacement of the box-shaped steel column increases. The influence parameters should be reasonably designed to improve the blast resistance ability of box-shaped steel columns.

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References
[1] Magallanes, J.M., Martinez, R., Koenig, J.W. (2006) Experimental results of the AISC full-scale column blast test [R]. Karagozian & Case.
[2] Chen, H., Liew, J.Y.R. (2005) Explosion and fire analysis of steel frames using mixed element approach [J]. Journal of Engineering Mechanics, 131(6):606-616.
[3] Liew, J.Y.R., Chen, H. (2004) Explosion and fire analysis of steel frames using fiber element approach [J]. Journal of Structural Engineering, 130(7):991-991.
[4] Zhang, Y., Zhang, X.H. (2014) Study on dynamic response and stability research of high-strength H section steel column under blast loading [D]. Harbin: Northeast Forestry University.
[5] Zhang, X.H. (2014) Dynamic response and influence factor analysis of steel columns under blast Loading [J]. Journal of Disaster Prevention and Mitigation Engineering, 34(1): 73-84.
[6] Zhang, X.H. (2009) Numerical simulation on impact responses and failure modes of steel frame structural columns subject to blast loads [J]. Journal of Shenyang Jianzhu University: Natural Science Edition, 25(4):656-662.
[7] Li, G.Q., Yan, H.Y., Yang, T.C. (2014) Experimental study of concrete-filled steel tubular columns under blast loading [J]. Journal of Building Structures, 34(12): 69-76.
[8] Li, G.Q., Sun, J.Y. (2006) Research on the characteristics of SRC columns subjected to blast loading [D]. Shanghai: Tongji University.
[9] Qian, G.J. (2016) Study on the performance of box-shaped steel columns under blast loading [D]. University of Jinan.