Structural Optimization of Road Fully Enclosed Sound Barrier Based on Three-Dimensional Finite Element Analysis

Yang jingqiang1,*, Din dewei1 and Yang zhimian2
1CCCC First Harbor Engineering Co. Ltd, Tianjin, China
2School of transportation and logistics engineering, Wuhan University of technology, Wuhan, Hubei, China
Email: 2321547575@qq.com

Abstract. With the help of the finite element analysis software ANSYS, this paper establishes a finite element model of a fully enclosed sound barrier of elevated road, calculating and analyzing the stress of supporting structure under different working conditions, checking the strength, stiffness and stability of the structure under the most unfavorable working condition. Finally we optimize the structure according to its characteristics.

Keywords. Fully enclosed sound barrier; ANSYS software; Bearing capacity analysis; Structural optimization

1. Introduction
Since entering the 21st century, transportation has been developing rapidly in cities, but it follows the traffic noise problems[1]. The sound barriers have advantages of obvious noise reduction effect, flexible building processing, small land occupation and easy maintenance[2]. Therefore, setting sound barriers on both sides of the road to control traffic noise is a method that has been widely applied and praised at home and abroad.

For the roads with high-rise sound sensitive buildings along the line, the fully-enclosed sound barriers have obvious advantages over the semi-enclosed sound barriers[3]. The former can increase the sound insertion loss and finally effectively reduce the sound pressure level at the sound receiving point of high-rise floors.

Most of the sound barriers have the characteristics of light weight and large windward surface, they are more significantly affected by the wind than ordinary buildings. Compared with semi-enclosed sound barriers, fully-enclosed sound barriers have a closed top, which intensifies the adverse impact of snow load. Therefore, under the limit state of bearing capacity, the barrier structure shall not show excessive stress or deformation that may pose a threat to vehicles passing inside and make people feel uneasy. From what has been discussed above, the barriers should have the ability to resist various natural disasters such as wind, snow and earthquake, so it is very necessary to calculate and analyze the structure[4].

2. Model building
Based on the single lane ramp of urban elevated road and combined with existing engineering examples, this paper designs the following sound barriers[5]: the fully enclosed sound barrier adopts the form of portal frame, with a total length of 120m, a clear height of 5m, a maximum height of 5.6m and a width of 8m. The steel structure is used as the supporting structure, a portal steel frame is set every meter, and the top purlin is erected on the top to connect and bear the weight of the top plate. As the sound barrier itself is a wind sensitive building, H-section steel with strong bending bearing capacity is selected as the steel...
frame column. The steel brand is Q235, and the section size is 250mm × 250mm × 9mm × 14mm. Welding structure is adopted between columns and between columns and panels; The bottom of two rows of vertical columns is fixed with concrete.

Since the length of the sound barrier is 120m, if the full-length barrier structure is selected as the research object, the amount of analysis will be too large, which is not conducive to calculation. According to the structural characteristics of the sound barrier, it can be regarded as an infinite body. We select a 12m long sound barrier as the research object, imposing boundary conditions, and considering the influence of other parts on the selected section. The finite element model is shown in Figure 1.

![Finite element model of fully enclosed sound barrier](image)

**Figure 1.** Finite element model of fully enclosed sound barrier

In ANSYS software, beam188 element is used to simulate steel frame and purlins, and shell63 element is used to simulate panels[6]. The element material parameters are shown in Table 1.

| Component name          | columns and purlins | Sound absorption and insulation panel |
|-------------------------|---------------------|--------------------------------------|
| Material                | Q235 steel          | Aluminum alloy composite plate       |
| Element type            | Beam188             | Shell63                               |
| Elastic modulus         | 2.06 × 10¹¹Pa       | 7.2 × 10¹⁰Pa                         |
| Poisson's ratio         | 0.3                 | 0.33                                 |
| Density                 | 7.85 × 10³kg/m³     | 2.8 × 10³kg/m³                       |

3. Calculation and analysis

The structural stress calculation and analysis of the fully enclosed sound barrier includes the effects of self weight, wind load, snow load and seismic load. Different loads are applied through ANSYS software to calculate the axial force, shear force, bending moment and stress value distribution of the structure under various working conditions and analyze the most unfavorable position and the safety performance of the barrier structure. The load cases are shown in Table 2.

| working condition | Load combination                                         |
|-------------------|----------------------------------------------------------|
| Condition I       | Dead weight                                              |
| Condition II      | Dead weight + snow load                                   |
| Condition III     | Dead weight + wind load                                   |
| Condition IV      | Dead weight + snow load + wind load                       |
| Condition V       | Dead weight + seismic load                                |
The structural displacement and deformation under various working conditions and the positions needing attention can be calculated by ANSYS software as shown in Table 3.

**Table 3. Summary of working conditions**

| working condition | Maximum displacement (mm) | Maximum displacement position | Other positions needing attention |
|-------------------|---------------------------|-------------------------------|---------------------------------|
| Condition I       | 4.165                     | Middle of roof                | Curved panel                   |
| Condition II      | 5.889                     | Middle of roof                | Curved panel, connection between curved panel and side plate |
| Condition III     | 4.912                     | Windward top plate close to the middle | Connection between curved panel and side plate |
| Condition IV      | 5.806                     | Windward top plate close to the middle | Connection between top plate and curved plate, bottom of steel frame column |
| Condition V       | 4.313                     | Middle of roof                | Connections between top and curved plates |

It can be seen from table 3 that under condition 2, i.e. snow load, the maximum displacement is in the middle of the roof which is 5.889mm. According to the stress of the barrier structure, condition 4, i.e. wind and snow combined load, is the most unfavorable condition, and the displacement in the middle of the top plate is 5.806mm. The reason why the displacement in the middle of the roof in condition 4 is less than that in condition 2 is that for the double slope roof, the wind load will produce a certain suction on the roof on the windward side, which reduces the vertical displacement of the roof to a certain extent.

Under the combined wind and snow load, the displacement nephogram of condition 4 is shown in Figure 2. The maximum displacement is 5.806mm, which is near the middle of the roof on the windward side. The displacement of the windward side plate is very small, almost 0; The maximum displacement of the side plate on the leeward side is 2.58mm, which is at the connection between the curved plate and the side plate.

![Cloud diagram of displacement under working condition IV](Image)

**Figure 2. Cloud diagram of displacement under working condition IV**

4. **Structural checking calculation**

The checking calculation of the bearing capacity limit state of the supporting steel frame under the most unfavorable working condition mainly includes three aspects: strength, stiffness and stability.

According to the results obtained by ANSYS software, the maximum compressive stress appears at the bottom of the steel frame column, and the maximum compressive stress is 1298400pa. The maximum tensile stress appears on the cross beam at the connection position between side plate and curved plate, and the maximum tensile stress is 283120pa. The maximum compressive stress and maximum tensile stress are far less than the design value of compressive and tensile strength of Q235.
steel 215000000pa. The strength checking calculation meets the requirements. The stress table of steel frame column is shown in Table 4. The negative sign indicates compressive stress, otherwise it is tensile stress.

| Element number | Section stress (Pa) |
|----------------|---------------------|
| 441            | -1 298 400          |
| 442            | -1 100 000          |
| 443            | -990 360            |
| 444            | -918 830            |
| 445            | -863 730            |
| 446            | -816 940            |
| 447            | -771 160            |
| 448            | -720 130            |
| 449            | -670 340            |

Table 4. Stress of steel frame column (Pa)

The stiffness of compression bending members is usually determined by slenderness ratio to measure. The smaller the slenderness ratio, the greater the stiffness of the member, and vice versa. Calculated slenderness ratio of column $\lambda = 14.58$, less than 150 allowable slenderness ratio of compression member column in “Code for design of building steel structures” (GB 50017-2003); The slenderness ratio of top purlin and beam is calculated $\lambda = 34.99$, less than the allowable slenderness ratio of tie bar of tension member 400. The stiffness checking calculation meets the requirements.

The criterion to avoid local instability of members is to make the local buckling critical stress greater than the yield strength of steel or the overall stability critical stress of members. In fact, the requirement of ensuring local stability is realized by limiting the width thickness ratio of plates. After calculation, the width thickness ratio of both flange and web are less than the specification limit. The stability checking calculation meets the requirements.

5. Structural optimization

5.1. Column section optimization

The column of barrier steel frame is mainly under pressure, and the maximum stress value is less than the compressive design strength of Q235 steel. Therefore, the section can be optimized. Considering the overall stability of the column, in order to avoid flexural-torsional buckling, the solid-web compression members generally adopt biaxial symmetric section.

The specific steps for designing sections are as follows:

1) Determine the size of the cross-sectional area: assume the slenderness ratio of the member $\lambda$ is 100. According to the classification of axial compression members in the “Technical code for steel structures of high rise civil buildings” (JGJ 99-1998), it is found that when the plate thickness $t$ of H-section steel is less than 80mm, the x-axis is class B section and the y-axis is class C section, which can be obtained by referring to the attached table $\phi_x = 0.581, \phi_y = 0.483, \phi_{min} = \phi_y = 0.483$. It can be calculated that $f = 215\text{MPa} = 215\text{N/mm}^2$. Then the required cross-sectional area is calculated as follows:

$$A = \frac{N}{\phi t} \quad (1)$$

$N$ — the force added to the section;

$\Phi$ — Overall stability coefficient;

$f$ — Steel compression strength design value.
The results of Chapter III are preliminarily brought into the available data: $A = 17.76\text{cm}^2$.

2) Calculate the rotation radius of the two spindles. The rotation radius of the two spindles is calculated according to the following formula:

\[ i_x = \frac{l_{ox}}{\lambda} \quad (2) \]
\[ i_y = \frac{l_{oy}}{\lambda} \quad (3) \]

- $i_x$ — Radius of gyration to X axis;
- $l_{ox}$ — Calculated length in x-axis direction;
- $\lambda$ — Slenderness ratio;
- $i_y$ — Radius of gyration to Y-axis;
- $l_{oy}$ — Calculated length in Y-axis direction.

Given $l_{ox} = l_{oy} = 5m$, $\lambda = 100$, it can be calculated that $i_x = i_y = 0.05m = 5cm$.

3) Cross sectional area $A$ and radius of gyration $i_x, i_y$ are obtained in the previous two steps. It is impossible to select from the list of common H-shaped steel to meet the requirements of $A_{req}, i_{xreq}, i_{yreq}$ at the same time. We can choose mainly $A_{req}, i_{yreq}$ and supplemented by $i_{xreq}$. According to the table, the size should be $250 \times 250 \times 9 \times 14$ (mm) HW section steel with the same size as the model.

4) Section checking calculation: the strength, stiffness and stability of steel frame column of this size has been checked in the previous chapter and meets the specification requirements, so the $250 \times 250 \times 9 \times 14$ (mm) HW section steel is the optimal size of the column.

Although the column section stress is surplus, in order to meet the requirements of overall stability, we cannot replace it with a smaller section.

5.2. Optimization of top purlin

The top purlin and beam are mainly subjects to bending tension, without bending instability or bending torsional buckling. The axial tension and the section maximum stress is small. Therefore, the round pipe bars can be selected for the top purlins, with the size of $\varphi 114 \times 4$ (mm), the section parameters are shown in the figure3.

By modifying the section type data in ANSYS software, it can be calculated that the maximum tensile stress of the section of the top purlin and beam is 284050pa, and it appears in the cross beam at the connection of side plate and curved plate, which is less than the tensile strength design value of Q235 steel. The cross-sectional area of round tubular steel is 13.82cm², while it is 92.18cm² for the H-shaped beam. The area is reduced by 78.36cm², a decrease of about 85%. After optimization, not only steel is saved, but also self weight is reduced.

![Figure 3. Cross section of top purlin round tubular steel](image-url)
6. Conclusion
1) According to the load code for buildings and structures, the displacement and stress distribution of the structure under five working conditions: self weight, snow load (including uneven distribution), wind load, wind snow combination and seismic load are calculated. The calculation results under five working conditions are summarized and analyzed to determine the most unfavorable working condition and the weak positions. The most unfavorable working condition is the combination of wind and snow load, and the weak positions include the bottom of the columns and the steel frame at the curved panel.
2) The strength, stiffness and local stability of the steel frame under the most unfavorable working condition and the bearing capacity limit state are checked, which meet the requirements of the code.
3) Combined with the calculation and analysis results and ANSYS software, the barrier steel frame structure is designed and optimized. In order to meet the requirements of overall stability, the column cannot be replaced with a smaller section. The top purlin and cross beam can replace the H-section steel with the round tubular one, so as to achieve the purpose of material saving and economy.

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