A Case Study of Finite Element Check for the Strength and Rigidity of the Escalator Truss

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Abstract. As an important part of escalator, the truss must be checked for strength and rigidity after design. In this paper, the finite element method is used to check the strength and rigidity of an escalator truss under various working conditions. Compared with the traditional design method, the finite element analysis can obtain the mechanical properties of the object quickly and accurately, shorten the project development time, and thus reduce the design and test cost greatly.

Keywords: Escalator truss; finite element; strength; rigidity.

1. Basic Structure of Escalator Truss
The escalator is a fixed electric-driven device with a series of circulating steps for conveying passengers in an upward or downward direction[1]. Since an escalator can transport passengers continuously, it has large transportation capacity, and can transport 4500-13500 people per hour[2]. Therefore, escalators are widely used in subway and railway station, airport, shopping mall and other crowded places. But the escalators are dangerous in some cases, they have been listed in the catalogue of the special equipment by Chinese government[3], and supervised by special regulations and standards.

The supporting structure of escalator, also known as truss, is the main metal structure of an escalator. The main structure of truss is generally made up of different kinds of metal components by welding or bolt connection, as shown in Fig.1. The escalator truss is generally welded by end joists, upper and lower chords, diagonal members, beams, bottom sealing plates and their supports, intermediate supports, lifting parts and other supports[4]. At present, most of the trusses of escalators are welded and made of carbon steel profiles, generally using angle steel and hollow square steel as the main materials.

2. Loading Characteristics of Escalator Truss
The escalator truss is used to install and support all parts of the escalator, bears all kinds of loads and connects the two different floors of the building. It is the carrier of transporting passengers. The ladder road, driving device, tensioning device, guide rail system and handrail device are installed in/on the truss, so the strength and rigidity of the truss play a very important role in the safety, reliability and comfort of the escalators. GB 16899-2011 safety rules for the manufacture and installation of escalators and moving walks[5] stipulates that the maximum deflection of escalators and moving walks shall not be greater than 1/750 of the supporting distance when they bear a uniform load of
5000N/m², while for public transportation escalators, the deflection shall not be greater than 1/1000 of the supporting distance.

According to the structural and operation conditions, the loads borne by escalators are mainly as follows:

(1) Uniform load. It mainly refers to the gravity of guide rail, handrail, apron, cover plate and other components.

(2) Passenger load. The design passenger load of truss is 5000N/m² according to national standard GB 16899-2011 safety rules for the manufacture and installation of escalators and moving walks.

(3) Concentrated load. It mainly refers to the integrated load of the components of the driving device, such as the driving machine and the control cabinet.

(4) Truss weight.

The escalator truss is affected by bending moment and torque at the same time, and the strength can be calculated according to the following combination of bending and torsion.

\[ \sigma_e = \frac{M_e}{W} \leq [\sigma] \]

In the above formula:

- \(M_e\) refers to equivalent bending moment, could be calculated by: \( M_e = \sqrt{M^2 + (\alpha \cdot T)^2} \), \( \alpha \) depends on the characteristics of torsion shear stress. In this case, it is considered that the torsion shear stress changes according to the fluctuating cycle, and \( \alpha = 0.6 \).
- \(W\) refers to bending section coefficient (mm³).

3. Finite Element Calculation of Typical Truss

The escalator has the characteristics of heavy load, long-time operation, wide range of environmental temperature and humidity, furthermore, its failure will endanger the safety of passengers, so bearing components (such as truss, steps, etc.) must have high reliability. The traditional design method based on experience usually makes the overall structure of escalator bulky. In order to adapt to the design concept of energy conservation and environmental protection and reduce the cost of materials, escalator lightweight design has become the development trend of the industry in recent years. The lightweight concept puts forward higher requirements for the design of its main load-bearing components, that is, to reduce the material and cost as much as possible to meet the strength requirement. Therefore, the traditional design method based on experience or simple theoretical calculation can not accurately grasp the mechanical properties of escalator load-bearing components, and other analysis or test methods are needed. In recent years, with the popularization of computer analysis technology, the finite element analysis method has been widely used in the analysis of structural strength of escalator truss, which can quickly and accurately obtain the mechanical characteristics of the analysis object, and could greatly reduce the design cost and test cost. He Xianxue et al. [6] used finite element method to analyze the influence of different sizes of profiles, the design layout of single middle section, and the section size of truss on the mechanical properties of truss. Tang Libo[7] explored the method of using CAE tools to improve the development efficiency of escalator through specific cases, and introduced the application of truss structure optimization method.

By using the finite element analysis, Liu Yanhui et al.[8] established the relationship between the pre-stress loss value and the deflection value at the observation point of the truss structure.

In this paper, a typical commercial escalator with a lifting height of 4.5m and an incline angle of 30 degrees is taken as the research object, the stress and the deflection of the truss under different working conditions are calculated by the finite element method.

The escalator truss is based on 2D geometric model. The truss inclined section is about 10 meters long, which is spliced by three boom sections. The structure is mainly composed of square tube, angle steel. In this paper, the strength and deflection of the escalator truss under the condition of self weight, full load and no load are analyzed. It preliminarily judges whether the escalator design meets the design requirements, makes it meet the requirements of the industry standards, and provides the improvement direction. Therefore, it could reduce the unnecessary loss caused by unreasonable design and shorten the development time.
The basic parameters of the study object are shown in Table 1, and the basic model is shown in Fig.1.

**Table 1.** The basic parameters of truss.

| parameters                        | symbol | value |
|-----------------------------------|--------|-------|
| Truss self weight /kg             | P      | 1661  |
| Uniform load of top chord /(kg/m) | Y1     | 234.5 |
| Uniform load of bottom chord /(kg/m) | Y2    | 210.5 |
| Passenger load /(N/m)             | Q      | 2.5   |

**Figure 1.** The basic parameters of truss model.

The material of truss square pipe is Q235, the material of angle steel is Q345B, and the material of handrail shaft is 45# steel. The physical parameters are shown in Table 2.

**Table 2.** The material property parameters of truss and main shaft.

| Material | Density $\rho$ (g/cm$^3$) | Young's modulus $E$ (MPa) | Poisson's ratio $\nu$ | Yield strength (MPa) | Tensile strength |
|----------|---------------------------|---------------------------|----------------------|----------------------|------------------|
| Q235     | 7.85                      | 210000                    | 0.3                  | 235                  | 400              |
| Q345B    | 7.85                      | 210000                    | 0.3                  | 345                  | 550              |
| 45#      | 7.85                      | 210000                    | 0.3                  | 355                  | 600              |
| QT400    | 7.85                      | 210000                    | 0.3                  | 250                  | 400              |

Altair HyperWorks 13.0 is used in the finite element simulation in this paper. HyperWorks is an innovative and open enterprise CAE platform. It integrates various kinds of tools needed for design and analysis. It has high performance, high openness, flexibility and friendly user interface, powerful modeling tools and simple pre-processing and post-processing modules.

This paper will focus on the analysis of the strength and rigidity of the escalator truss under the following three conditions:

1. **Working condition I:** When there is no passenger on the escalator, use HyperWorks static analysis to check the results of square pipe and angle steel;
2. **Working condition II:** When the elevator truss is full of passengers, use HyperWorks static analysis to check the results of square pipe and angle steel;
3. **Working condition III:** Only passengers, use HyperWorks static analysis to check the results of square pipe and angle steel.

During the finite element calculation, according to the installation characteristics of escalators, the X and Y directions of the lower station are constrained, and the Y direction of the upper station is constrained, as shown in Fig.2. Static loading is shown in Fig.3.
4. Truss Strength Analysis and Results
Through simulation, the strength and stiffness analysis of the upper and lower trusses under the above three conditions are obtained. In this simulation, the truss frame not including the base plate, and the angle steel is only the ones at both ends of the elevator. The summary of calculation results are shown in Table 3, and Fig. 4 shows the maximum deflection of truss frame under condition 2. The maximum deflection is 11.26 mm, which is also the maximum deflection in three conditions.

Table 3. The summary of calculation results.

| working condition               | maximum deflection (mm) | stress (MPa) |
|--------------------------------|-------------------------|--------------|
|                                | +X direction | -X direction | -Y direction | resultant deflection | framework | supporting angle steel |
| condition I (truss self weight) | 0.95         | -1.70        | -6.15        | 6.22                |           |                           |
| condition II (truss self weight plus passengers) | 1.73         | -3.13        | -11.14       | 11.26               | 71.2      | 79.8                      |
| condition III (only passengers) | 0.78         | -1.43        | -4.99        | 5.04                | 32.2      | 34.2                      |

Figure 4. Maximum deflection of truss frame under working condition II.
According to the requirement of GB 16899-2011, the maximum allowable deflection of truss is 1/1500 of its span when the escalator is fully passenger loaded. In the case of this paper, the maximum deflection of truss frame is 11.26mm, less than the maximum allowable deflection of escalator truss which is 11167/750 =14.89mm, which meets the design requirements. We should note that, if the escalator is used in the public transportation, the maximum allowable deflection is 11167/1000=11.17mm, therefore this escalator can't meet the public transportation escalator's requirements.

The maximum stress values of truss framework and angle steel are 71.2Mpa and 79.8Mpa respectively, not exceeding the allowable stress of 235Mpa, and the safety factor is 5.62, which is greater than the target value of 5, meeting the design requirements.

5. Summary
The strength and rigidity of the truss of the escalator play very important role in the safe operation of the escalator. After the completion of the product design, the strength and rigidity must be checked and compared to see if they meet the relevant requirements.

In this paper, the finite element method is used to check the strength and rigidity of the truss design of an escalator. The calculation results show that the design meets the requirements of GB 16899-2011, but this escalator can't meet the requirements of public transportation.

Through the case of this paper, it can be shown that compared with the traditional design method based on experience or simple theoretical calculation, the finite element analysis method can obtain the mechanical characteristics of the analysis object quickly and accurately, and shorten the project development time, thus reduce the design cost and test cost greatly.
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