Index evaluation of overall stability of small-span steel plate bridge

Haoqi Li
School of Highway, Chang’an University, Xi’an, China
Corresponding author email: lhq@chd.edu.cn

Abstract. Based on a 3×35m steel plate bridge of a highway project, a nonlinear entity model is established using finite element software, and the structure is evaluated with the stability safety factor as the evaluation index. Through the analysis of different parameters, some conclusions are drawn to satisfy the stability of the bridge structure.

1. Introduction
With the rapid development of social economy and highway transportation, steel plate beam bridges with small and medium spans have been increasingly studied and applied. In the design of steel structures and composite structures, stability is an important point that must be considered. In the current code, only the formula for calculating the overall stability coefficient of I-shaped simply-supported beams and the relevant provisions on the limits of the width-to-thickness ratio of the wing and the height-to-thickness ratio of the web are given. Therefore, it is necessary to conduct in-depth analysis and research on the stability of small and medium span steel plate composite bridges.

2. Analysis method and content
Numerical analysis method: Elastoplastic stability analysis of ABAQUS finite element program.
Evaluation index: Stability was evaluated by stabilizing the structure of the safety factor. The second type of stability evaluation index is adopted, and the stability safety factor

$$\xi = \frac{F_s + \lambda F_c}{F_s + F_c}$$

(1)

Among them, $F_s$ is the weight of the steel beam, $F_c$ is the weight of the concrete bridge deck, and $\lambda$ is the loading coefficient.

3. Parametric analysis
This article analyzes the following parameters to get the effect on stability, as shown in Figure 1.
3.1. Beam spacing

According to the principle that under the same load, the stress levels of the upper and lower flanges of the steel beam and the structural bearing capacity are the same. By changing the beam spacing in the model, we got the following data.

Table 1. Calculation results of straight beam.

| Beam spacing / m | Load form  | Loading factor λ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange / Mpa | Instability mode               |
|------------------|------------|------------------|---------------------------------------|---------------------|------------------------------------------|-------------------------------|
| 35               | Uniform load | 2.9             | 107.5                                 | 2.47                | 345                                       | Lateral torsional instability |
| 17.5             | Uniform load | 6.9             | 239.8                                 | 5.52                | 345                                       | Lateral torsional instability |
| 11.67            | Uniform load | 8               | 275.5                                 | 6.34                | 345                                       | Lateral torsional instability |
| 8.75             | Uniform load | 8.9             | 306.9                                 | 7.06                | 345                                       | Web flexion                   |
| 7                | Uniform load | 9               | 309                                   | 7.11                | 345                                       | Web flexion                   |

Table 2. Calculation results of Curved beam.

| Radius / m | Beam spacing / m | Load form  | Loading factor λ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange / Mpa | Instability mode               |
|------------|------------------|------------|------------------|---------------------------------------|---------------------|------------------------------------------|-------------------------------|
| 460        | 35               | Uniform load | 2.4             | 88.7                                  | 2.04                | 345                                       | Web flexion                   |
| 460        | 17.5             | Uniform load | 5.1             | 117.9                                 | 4.1                 | 345                                       | Web flexion                   |
| 460        | 11.67            | Uniform load | 5.9             | 205.7                                 | 4.74                | 345                                       | Web flexion                   |
| 460        | 8.75             | Uniform load | 7.5             | 258                                   | 5.94                | 345                                       | Web flexion                   |
| 460        | 7                | Uniform load | 8.5             | 290.2                                 | 6.68                | 345                                       | Web flexion                   |

From the above chart, it can be found that as the distance between beams decreases, the stability safety factors of straight beams and curved beams gradually increase;
The stability limit bearing capacity and stability safety factor of beams with a spacing of 8.75m and 7m are almost the same. For 3 × 35m double I-shaped steel straight beams, from the perspective of stability, compared with the beam spacing of ≤7m commonly used in current engineering, the beam spacing of 8.75m can be used to meet the requirements of the specification.

3.2. **High span ratio**
According to the principle that under the same load, the stress levels of the upper and lower flanges of the steel beam and the structural bearing capacity are the same, the size of the upper and lower wing plates is changed as the beam height changes.

| High span ratio | Load form | Loading factor λ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|-----------------|-----------|------------------|--------------------------------------|---------------------|------------------------------------------|------------------|
| 1/18            | Uniform load | 9.1              | 310.7                                | 7.15                | 345                                      | Web flexion     |
| 1/19.44         | Uniform load | 9                | 309                                  | 7.11                | 345                                      | Web flexion     |
| 1/21            | Uniform load | 8.3              | 285                                  | 6.59                | 345                                      | Web flexion     |
| 1/24            | Uniform load | 7.8              | 269.3                                | 6.19                | 345                                      | Web flexion     |
| 1/27            | Uniform load | 7.5              | 259                                  | 5.91                | 345                                      | Web flexion     |

| Radius /m       | High span ratio | Load form | Loading factor λ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|-----------------|-----------------|-----------|------------------|--------------------------------------|---------------------|------------------------------------------|------------------|
| 460             | 1/18            | Uniform load | 9.4              | 318.2                                | 7.32                | 345                                      | Web flexion     |
| 460             | 1/19.44         | Uniform load | 8.5              | 290.2                                | 6.68                | 345                                      | Web flexion     |
| 460             | 1/21            | Uniform load | 8                | 271.5                                | 6.3                 | 345                                      | Web flexion     |
| 460             | 1/24            | Uniform load | 7.1              | 243.5                                | 5.6                 | 345                                      | Web flexion     |
| 460             | 1/27            | Uniform load | 5.6              | 193.5                                | 4.39                | 345                                      | Web flexion     |

It can be seen from the Figure 3 and 4, as the high-span ratio decreases, the stability and safety factor of the structure gradually decreases, and the two are basically in a linear relationship; the stability safety factor of curved beams is more affected by the high-span ratio; Comprehensive stability and safety and economic performance factors, for small and medium-span double-steel composite continuous beam bridge, it is recommended to adopt a high-span ratio of about 1/20.

3.3. **Width-thickness ratio**
By changing the width-thickness ratio in the model, we got the following data.
Table 5. Calculation results of straight beam.

| Width-thickness ratio | Load form | Loading factor λ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|-----------------------|-----------|-------------------|---------------------------------------|---------------------|------------------------------------------|-----------------|
|                       |           |                   |                                       |                     |                                          |                 |
| 8                     | Uniform load | 9.3               | 317.6                                 | 7.33                | 345                                      | Web flexion     |
| 10.7                  | Uniform load | 9                 | 309                                   | 7.11                | 345                                      | Web flexion     |
| 13                    | Uniform load | 8.8               | 299.5                                 | 6.91                | 345                                      | Web flexion     |
| 14                    | Uniform load | 7.4               | 255.5                                 | 5.89                | 345                                      | Web flexion     |
| 15                    | Uniform load | 7.5               | 256.7                                 | 5.93                | 345                                      | Flap buckling   |
| 17                    | Uniform load | 7.4               | 254.7                                 | 5.87                | 345                                      | Flap buckling   |

Table 6. Calculation results of curved beam.

| radius /m | width-thickness ratio | Load form | Loading factor λ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|------------|-----------------------|-----------|-------------------|---------------------------------------|---------------------|------------------------------------------|-----------------|
| 460        | 8                     | Uniform load | 8                | 274.4                                 | 6.33                | 345                                      | Web flexion     |
| 460        | 10.7                 | Uniform load | 8.5              | 290.2                                 | 6.68                | 345                                      | Web flexion     |
| 460        | 13                   | Uniform load | 8.8              | 300.3                                 | 6.92                | 345                                      | Web flexion     |
| 460        | 14                   | Uniform load | 8.7              | 296.6                                 | 6.85                | 345                                      | Web flexion     |
| 460        | 15                   | Uniform load | 8.6              | 292.5                                 | 6.76                | 345                                      | Web flexion     |
| 460        | 17                   | Uniform load | 8.4              | 285.3                                 | 6.58                | 345                                      | Web flexion     |

Figure 5. Relationship between stability coefficient and aspect ratio.

From the Figure 5, it can be seen that with the increase of the width-to-thickness ratio of the compressed flange, the stability safety factor of the straight beam gradually decreases, and the stability safety factor of the curved beam is basically unchanged.

For straight beams, local buckling of steel beams will occur in relatively weak areas of both the compressed flange and the web. Studies have shown:

When the height-to-thickness ratio of the web is 50 to 80, the width-to-thickness ratio of the compressed flange can be calculated according to Equation:

\[
\frac{b}{t} = 0.02119 \left( \frac{h_o}{t_f} - 34.685 \right)^2 + 19.177
\]

When the height-to-thickness ratio of the web is less than 50, the width-to-thickness ratio of the compressed flange is taken as 12 according to specifications;

When the height-to-thickness ratio of the web is greater than 80, the width-to-thickness ratio of the compressed flange may be the minimum value that meets the requirements of the stress, the construction, and the arrangement of the shear pins.

3.4. High thickness ratio

By changing the high thickness ratio in the model, we got the following data.
Table 7. Calculation results of straight beam.

| High thickness ratio | Load form | Loading factor $\lambda$ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|----------------------|-----------|--------------------------|--------------------------------------|---------------------|---------------------------------------------|------------------|
| 64                   | Uniform load | 9                       | 309                                  | 7.11                | 345                                         | Web flexion      |
| 80                   | Uniform load | 8.4                     | 287.9                                | 6.64                | 345                                         | Web flexion      |
| 100                  | Uniform load | 7.7                     | 265.6                                | 6.13                | 345                                         | Web flexion      |
| 120                  | Uniform load | 7.2                     | 248.8                                | 5.74                | 345                                         | Web flexion      |
| 140                  | Uniform load | 6.7                     | 230.6                                | 5.32                | 345                                         | Web flexion      |
| 160                  | Uniform load | 5.9                     | 206.2                                | 4.76                | 345                                         | Web flexion      |

Table 8. Calculation results of curved beam.

| radius /m | High thickness ratio | Load form | Loading factor $\lambda$ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|-----------|----------------------|-----------|--------------------------|--------------------------------------|---------------------|---------------------------------------------|------------------|
| 460       | 64                   | Uniform load | 8.5                     | 290.2                                | 6.68                | 345                                         | Web flexion      |
| 460       | 80                   | Uniform load | 7.4                     | 256.2                                | 5.9                 | 345                                         | Web flexion      |
| 460       | 100                  | Uniform load | 6.2                     | 214.8                                | 4.94                | 345                                         | Web flexion      |
| 460       | 120                  | Uniform load | 4.8                     | 166.6                                | 3.83                | 345                                         | Web flexion      |
| 460       | 140                  | Uniform load | 3.7                     | 132.4                                | 3.05                | 345                                         | Web flexion      |
| 460       | 160                  | Uniform load | 2.9                     | 106                                  | 2.44                | 345                                         | Web flexion      |

As can be seen from the Figure 6, as the height-to-thickness ratio of the web increases, the stability and safety factor of the structure gradually decreases, and the two are basically in a linear relationship; the stability safety factor of curved beams is more affected by the web height-thickness ratio.

3.5. Curvature radius

By changing the curvature radius in the model, we got the following data.

Table 9. Calculation results of curved beam.

| radius /m | Center angle /° | Load form | Loading factor $\lambda$ | Stable ultimate bearing capacity KN/m | Stable safety factor | Normal stress at mid-span upper flange /Mpa | Instability mode |
|-----------|-----------------|-----------|--------------------------|--------------------------------------|---------------------|---------------------------------------------|------------------|
| 1000      | 6               | Uniform load | 9                       | 309                                  | 7.11                | 345                                         | Web flexion      |
| 800       | 7.5             | Uniform load | 8.9                     | 305.4                                | 7.03                | 345                                         | Web flexion      |
| 600       | 10              | Uniform load | 8.8                     | 299.7                                | 6.9                 | 345                                         | Web flexion      |
| 500       | 12              | Uniform load | 8.7                     | 296.3                                | 6.82                | 345                                         | Web flexion      |
| 460       | 13.1            | Uniform load | 8.5                     | 290.2                                | 6.68                | 345                                         | Web flexion      |
| 200       | 30.1            | Uniform load | 6.7                     | 231.9                                | 5.34                | 345                                         | Web flexion      |
| 100       | 60.2            | Uniform load | 4.7                     | 165.3                                | 3.81                | 345                                         | Flap buckling    |
As it can be seen from Figure 7 and 8, with the increase of the radius of curvature, the structural stable safety factor increases. The factor grows faster when radius = 100~500m, and the growth is more stable when radius = 600~1000m. All of outer main beam are unstable first.

4. Conclusion

Except for the width-to-thickness ratio of the compressed flange, the stability and safety of 3 × 35m straight beams are better than curved beams in the analysis of various parameters, and the stability and safety of curved beams are more affected by various structural parameters.

For 3 × 35m straight beams, from the perspective of stability, it is recommended to consider the 8.75m beam spacing to save steel.

From the comprehensive consideration of structural stability, safety and steel consumption, it is recommended that the high-span ratio of medium-small-span steel plate beams is 1/20.

Local buckling will occur in the relatively thin positions of the compressed flange and the web. The value of the width-to-thickness ratio of the compressed flange of the straight beam is suggested.

References

[1] Nie J, Liu M, Ye L. (2005) Steel plate structure [M]. China Construction Industry Press.
[2] Ministry of Housing and Urban-Rural Development of the People's Republic of China. (2017) National Standards of the People's Republic of China. Code for Design of Steel Structures [M]. China Planning Press.
[3] Cao P. (1999) Study on the limit value of the height-to-thickness ratio of steel beam webs without stiffeners [J]. Steel Structures.
[4] Yuan M. (2005) Study on transverse normal stress and overall stability of steel plate beams [D]. Hehai University.
[5] Liu H, Zhu B, Cao P. (2006) Calculation and analysis of the overall stable bearing capacity of two-span continuous beams [J]. Steel Structure.
[6] Li X. (2007) Study on the stability of steel plate beams [D]. Central South University.
[7] Wang L. (2009) Overall stability analysis of welded I-section composite steel beam webs after buckling [D]. Xinjiang University.
[8] Chen S. (2013) Guidelines for Design of Steel Structure Stability (Third Edition) [M]. China Construction Industry Press.
[9] Ministry of Transport of the People's Republic of China. (2015) Industry Standards of the People's Republic of China. Code for Design of Highway Steel Structure Bridges [S]. People's Communications Press.
[10] Wu B. (2015) Mechanical characteristics and finite element analysis of continuous curved beam bridges [D]. Southwest Jiaotong University.
[11] Fan L. (2001) Bridge Engineering (Vol. 1) [M]. People's Communications Press.
[12] Sun G. (1995) Calculation of curved beam bridge [M]. People's Communications Press.
[13] Yao L. (1982) Practical calculation method for curved beam bridges [J]. Journal of Civil Engineering.