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Stability Analysis of Long Span Steel Truss and Concrete Composite Continuous Rigid Frame Bridge in Finished Bridge State

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Abstract

To study the stability of long span steel truss and concrete composite continuous rigid frame bridge in finished bridge stage, based on structural stability theory, a spatial finite element model is established by large finite element software to analyze elastic stability of the whole bridge, and influences of design parameters as width-span ratio, stiffness of bridge pier and position of lateral bracing system are discussed on this basis. The results is shown as following: Dead load is the main factor and live load has less influence on structural stability, and main instability mode is out-of-plane instability. The local instability appears in the region of pier top, which is only influenced by slenderness of truss members. The out-of-plane and in-plane stability could be improved by increasing width-span ratio of bridge and stiffness of bridge pier. The position of lateral bracing system can be improved greatly the out-of-plane stability only.

Keywords: steel truss-concrete, composite frame, finished bridge state, elastic stability, parameter analysis.

1. Introduction

As an extension of composite truss bridge, steel truss and concrete composite continuous rigid frame bridge[1] can make good use of mechanical property of two materials. Concrete bridge decks are prefabricated, which can overcome the adverse effects of shrinkage and creep on long-term reliability of bridge, and construction period also can be shorten[2]. The whole bridge has a good integrity and spanning capacity, which conform to the general development trend of bridge construction in the world[3]. Therefore, steel truss and concrete composite continuous rigid frame bridge has become more and more favored by the designers.

There have been many studies on the stability of prestressed concrete continuous rigid frame bridge[4-6], but it is rarely in the study on the stability of steel truss and concrete composite continuous rigid frame bridge. The whole composite truss bridge is bended, but the truss members mainly sustain tension and compression. Compared with other types of continuous rigid frame bridges, there will appear truss members instability on steel truss and concrete composite continuous rigid frame bridge, which should deserve more attention on it. Therefore, a typical steel truss and concrete composite continuous

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rigid frame bridge with 386m main span is introduced as a project background, a spatial finite element model is established by large finite element software to analyze elastic stability of the whole bridge in finished bridge state, and influences of design parameters as width-span ratio, stiffness of bridge pier and position of lateral bracing system are discussed on this basis, in order to provide reference for the same typical bridge design in the future.

2. Stability analysis theory

Structural instability can be expressed by the following Eq. (1).

$$K_T \Delta u = (K_0 + K_L + K_\sigma)\Delta u = \Delta R \tag{1}$$

In Eq. (1), K_T is the tangent stiffness matrix of structure, which contains the stiffness matrix of element K_0, the stiffness matrix of initial displacement K_L and the stiffness matrix of initial stress K_σ. It is assumed that structure is in small deformation state before losing stability, then K_L equals 0. Meanwhile, it is assumed that all materials are in the elastic state, then K_σ has a linear relation with stress. Eq. (1) can be simplified as Eq. (2).

$$\left(K_0 + K_\sigma\right)\Delta u = \Delta R \tag{2}$$

A reference load $\overline{P}$ can be defined that match a corresponding stiffness matrix of initial stress $\overline{K_\sigma}$, then the critical load can be defined as $P_{cr} = \lambda \overline{P}$. While structure is in a critical state, even $\Delta R \to 0$, Δu still has a nontrivial solution, then Eq. (3) can be obtained.

$$\left|K_0 + K_\sigma\right| = 0 \tag{3}$$

The stiffness matrix of initial stress under the critical load is shown as following:

$$K_\sigma = \lambda \overline{K_\sigma} \tag{4}$$

Eq. (4) is substituted into Eq. (3), then Eq. (5) can be obtained.

$$\left|K_0 + \lambda \overline{K_\sigma}\right| = 0 \tag{5}$$

Eq. (5) is the governing equation of linear stability problem, then stability problem is converted to be a minimum eigenvalue problem of Eq. (1) [7].

In this equation, λ is the stability coefficient and the reference load $\overline{P}$ is defined as $1 \times \left(\text{dead load} + \text{live load}\right)$ [8].

3. Structural system and finite element model

3.1 Introduction of typical bridge

The span arrangement of a typical steel truss and concrete composite continuous rigid frame bridge is 193m+386m+193m, the girder is variable height truss, the girder height on the top of pier is 38m and in the middle span is 7m, and the line of lower chord members is parabolic. The bridge is divided into left part and right part, the bridge width of each part is 12m, the distance of main truss is 6m. The bridge decks make use of precast concrete slab and the thickness of slab is 60cm. The concrete decks combine with steel trusses through the shear connectors. Besides, the size of double-leg thin-walled pier is 7m× 3m. The details are shown as Fig.1 and Fig.2.

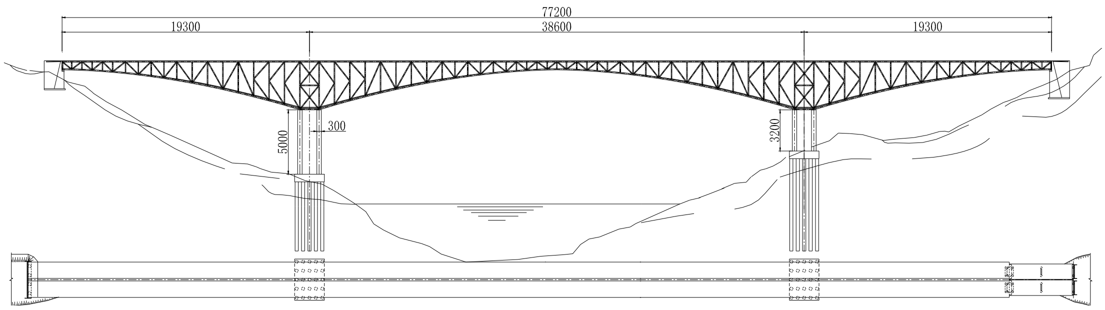

Fig.1. Diagram of typical bridge (unit: cm)

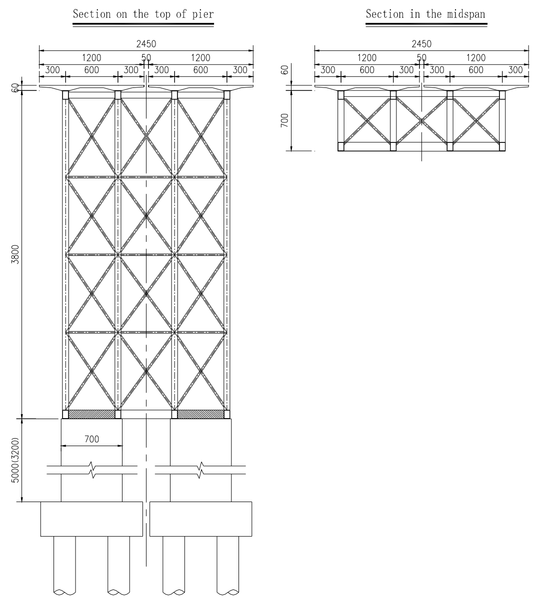

Fig.2. Cross section of typical bridge (unit: cm)

3.2 Finite element model

The finite element model of whole bridge is established by large finite element software Midas Civil 2012, all components of model are simulated by space beam element. The number of nodes is 1910 and the number of elements is 3321. The shear connectors between concrete decks and steel trusses are simulated by rigid connection.

In order to find the governing factor of structure instability and the degree of different live loading affect the stability in finished bridge state. Different conditions are discussed in this paper as following: (1) Condition 1: dead load only; (2) Condition 2: dead load and static wind load; (3) Condition 3: dead load and vehicle load; (4) Condition 4: dead load and the temperature rising; (5) Condition 5: dead load and the temperature cooling. The static wind load is calculated by the standard 《Wind-resistant Design Specification for Highway Bridges》(JTG/T D60-01-2004) [9].

3.3 Calculation result and analysis

As shown in Table 1, every condition meet the demands that the first order stability coefficient is greater than 5. Compared with condition 1, the first order stability coefficient decreased 3.0% in condition 2, decreased 7.1% in condition 3, and decreased 0.4% in condition 4 similarly, but increased 0.5% in condition 5. So dead load is the main factor affecting the stability of large span steel truss concrete composite continuous rigid frame bridge, live load has less influence on structural stability, the influence of vehicle load is worse than static wind load. In addition, the temperature rising is unfavorable for structural stability and the temperature cooling is favorable, but the effect of temperature change is very small in general.

Table 1. Different condition of stability coefficient and instability mode

Condition	Order	Stability coefficient	Instability mode
1	The first order	7.37	Out-of-plane lateral instability
	The second order	8.86	In-plane lateral instability
	The third order	12.88	Member instability on the top of pier
2	The first order	7.15	Out-of-plane lateral instability
	The second order	8.64	In-plane lateral instability
	The third order	12.50	Member instability on the top of pier
3	The first order	6.85	Out-of-plane lateral instability
	The second order	8.52	In-plane lateral instability
	The third order	12.03	Member instability on the top of pier
4	The first order	7.34	Out-of-plane lateral instability
	The second order	8.85	In-plane lateral instability
	The third order	11.98	Member instability on the top of pier
5	The first order	7.41	Out-of-plane lateral instability
	The second order	8.87	In-plane lateral instability
	The third order	13.94	Torsion instability

Fig.3. Mode of out-of-plane instability

Fig.4. Mode of in-plane instability

Fig.5. Mode of truss members instability on the top of pier

Fig.6. Mode of torsion instability

As shown in Fig.3 to Fig.6, the trend of instability mode is basically the same in these conditions, the out-of-plane instability always appears earlier than the in-plane instability. The reasonable explain is that steel truss concrete composite continuous rigid frame bridge has a long span and a small width-span ratio, so the transverse direction of bridge stiffness is much smaller than the longitudinal direction, then the structural instability appears towards to the weaker stiffness direction. Besides, truss members instability always appears in the region of pier top, then compression members in this region must be strengthened so that local stability could be improved.

4. Parameter analysis of influence factors

In order to study the stability influence factors of long span steel truss and concrete composite continuous rigid frame bridge with different design parameters, the typical bridge with a main span of 386m is taken as a study object, then width-span ratio, stiffness of bridge pier and position of lateral bracing system are chosen as influence factors, the stability coefficients of out-of-plane, in-plane and truss members are taken as the results which can reflect the bridge stability. Because dead load is the main factor that affecting the bridge stability, only the results of condition 1 are extracted for these parameter analyses.

4.1 Influence of width-span ratio

The width-span ratio changes through bridge width changes and bridge span keeps unchanged, then parameter analyses are based on different bridge width, the results are shown as Fig.7.

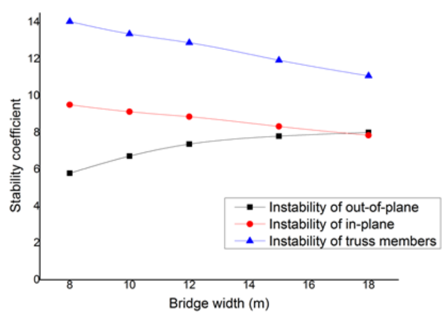

Fig.7. Influences of bridge width on stability coefficient

The first order stability coefficient increases by 35.6% with bridge width increasing, which is effective for improving the bridge stability. Instability coefficient of out-of-plane increases with bridge width increasing, but instability coefficient of in-plane decreases, and instability of in-plane appears earlier than out-of-plane while width-span ratio is greater than 0.047 (as bridge width is greater than 18m). The stability coefficient of truss members decreases with bridge width increasing, because slenderness of truss members increases while bridge width increasing, then the stability of compression member is reduced. [10]

4.2 Influence of pier stiffness

One of double-leg thin-walled pier is shown as Fig.8, the transverse direction of pier stiffness changes through length of pier changes, and the longitudinal direction of pier stiffness changes through width of pier changes, while the thickness of pier keep unchanged. The results are shown as Fig.9.

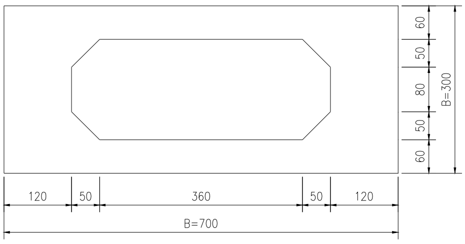

Fig.8. Dimension of pier (unit: cm)

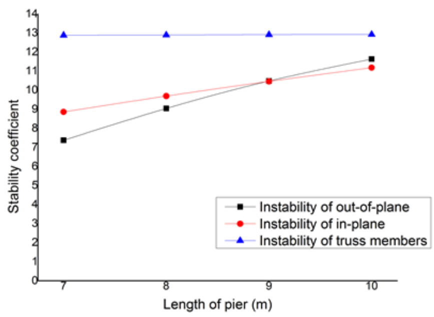

Fig.9. Influences of pier length on stability coefficient

The first order stability coefficient increases by 51.7% with length of pier increasing, which is effective for improving the bridge stability. Both of out-of-plane and in-plane stability coefficients increase with length of pier increasing, but the increasing trend of in-plane stability coefficient is less than out-of-plane, then instability of in-plane appears earlier than out-of-plane at last. Moreover, the stability coefficient of truss members is not impacted by length of pier.

The first order stability coefficient increases by 40% with width of pier increasing, which is also effective for improving the bridge stability. Both of out-of-plane and in-plane stability coefficients increase with width of pier increasing, but the increasing trend of out-of-plane stability coefficient is much greater than in-plane, then instability of in-plane is more difficult to appear. Moreover, the stability coefficient of truss members is not impacted by width of bridge pier, either.

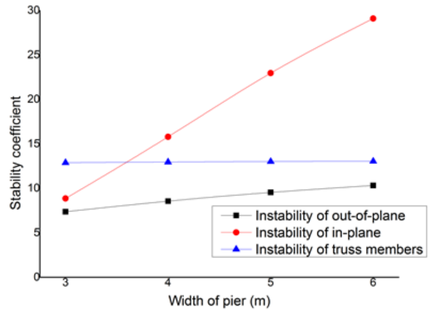

Fig.10. Influences of pier width on stability coefficient

4.3 Influence of lateral bracing system

The bridge is divided into left part and right part, in order to study the influences of stability with different lateral bracing, 4 lateral bracing systems are set up in the region of pier top, interquartile in the middle span, midspan in the middle span and all of the above, respectively. The position of lateral bracing systems are shown as Fig.11.

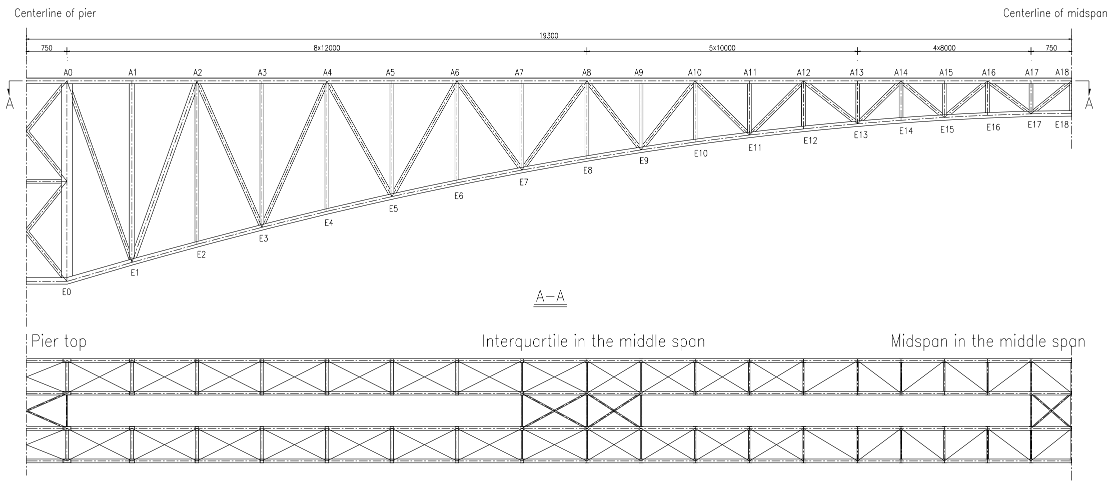

Fig.11. Position of lateral bracing system

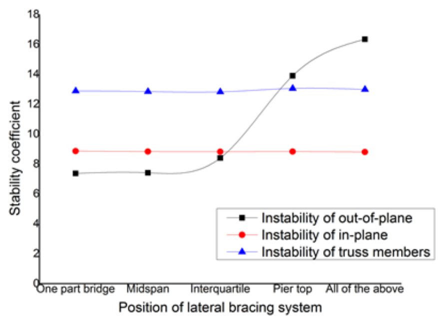

Fig.12. Influences of lateral bracing system on stability coefficient

As shown in Fig.12, the first order stability coefficient increases by 0.5%、14%、19.8% and 19.4% respectively with lateral bracing systems in the region of pier top, interquartile in the middle span, midspan in the middle span and all of the above. Lateral bracing system can only increase the stability coefficient of out-of-plane, the stability coefficients of in-plane and truss members are not impacted, due to lateral bracing system can improve the transverse direction of bridge stiffness only. In addition, the lateral bracing system is closer to the pier top, the bridge stability will improve more; the more lateral bracing systems are set up, the more bridge stability will improve.

5. Conclusion

Through the analysis and research on the stability of long span steel truss and concrete composite continuous rigid frame bridge, some results are listed as following:

(1) The stability of long span steel truss and concrete composite continuous rigid frame bridge has a certain law due to its own structural characteristics: Dead load is the main factor affecting the stability of bridge and live load has less influence on structural stability, the typical instability mode is out-of-plane instability.

(2) Member instability always appeared in the region of pier top, the stability coefficient is only impacted by slenderness of truss members, compression members in this region must be strengthened and slenderness of truss members should be reduced.

(3) Instability of out-of-plane improves with width-span ratio increasing, but instability of in-plane and truss members decrease at the same time. Instability of in-plane appears earlier than out-of-plane while width-span ratio is greater than 0.047 (as bridge width is greater than 18m), which must be noticed in the design process.

(4) Instability of out-of-plane and in-plane improve with pier stiffness increasing, and increasing the transverse direction of pier stiffness is better than increasing the longitudinal direction of pier stiffness. The stability of truss members is not impacted by pier.

(5) Instability of out-of-plane improves with lateral bracing system between two parts of bridge, but the stability of in-plane and truss members are not impacted. In addition, the lateral bracing system is closer to the pier top, the bridge stability will improve more; the more lateral bracing systems are set up, the more bridge stability will improve.

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