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Reliability analysis for lateral stability of tongwamen bridge

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Abstract. Tongwamen Bridge is a critical link between Dongmen Island and the land in Shipu town, Zhejiang province, China. It is a 238 m span, half-through, concrete-filled steel tubular (CFST) X-type arch bridge. The width of the deck is only 10 m, yielding a width-to-span ratio of 1/23.8. The plane truss type section rib was adopted, which made of two CFST chords and web member system. The lateral stability is the key issue to this bridge. However, the existing researches on Tongwamen Bridge's lateral stability are all the deterministic structural analysis. In this paper, a new strategy for positioning sampling points of the response surface method (RSM), based on the composite method combining RSM with geometric method for structural reliability analysis, is employed to obtain the reliability index of lateral stability. In addition the correlated parameters were discussed in detail to find the major factors. According to the analysis results, increasing the stiff of lateral braces between the arch ribs and setting the proper inward-incline degree of the arch rib can enhance obviously the reliability of lateral stability. Moreover, the deck action of non-orienting force is less than the two factors above. The calculated results indicate that the arch ribs are safe enough to keep excellent stability, and it provides the foundation that the plane truss rib would be a competitive solution for a long-span, narrow, CFST arch bridge.

Keywords: CFST bridge; stability; reliability ; response surface method (RSM), analysis

1.Introduction

Composite concrete-filled steel tubular (CFST) members are most suitable for structure where they are required to behave mainly under uniaxial compression. One of the advantages of this composite material is that of the steel can provide permanent integral formwork for the concrete infill. In the meantime, the strength of the concrete inside the tubular structure can be increased using the restraint of the steel tubes because of the different Poisson ratios of two materials. Thus it is convenient to erect and in addition the construction of a long-span arch bridge can be more economical (Zhang *et al.*2004).

After Wangcang East-river Bridge was built in 1990 in Sichuan province, the CFST arch bridges are now being increasingly used in the construction all over China, particularly long-span arch bridges. During the development of a highway bridge, we usually meet problems related to the length of the span and narrowness of the bridge. It is very important to ensure the feasibility and economic efficiency of the bridge. The practice of Tongwamen Bridge provides a good example for solving this solution.

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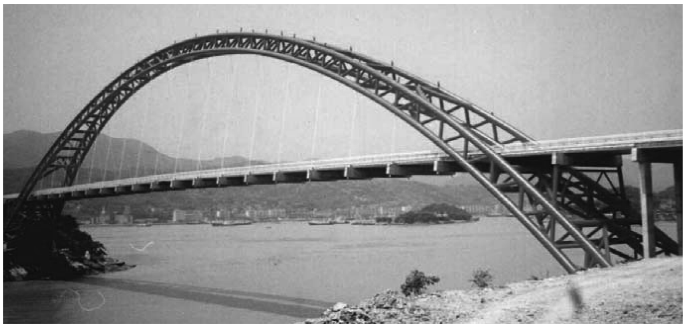


Fig. 1 Tongwamen bridge

Tongwamen Bridge is a critical link between Dongmen Island and the land in Shipu town, Zhejiang province, China. The depth of the water is more than 50 m at the site of the bridge, and the width is about 200 m. Both banks of the channel are very steep and consist of bare rock. On the basis of the natural conditions, a CFST, half-through, X-type arch bridge as the optimal scenario was adopted(Fig. 1). The existing features were instrumental in arriving at a span of 238 m with a span-depth ratio of 4.823. The axis of the rib is a modified second-degree parabola. However, the selection of the rib section is the key issue in design.

Taking account of the overall deck width being only 10m, the ribs were designed as plane trusses including CFST upper and lower chords and a tubular steel web system. In accordance with the analysis of strength, fatigue and stability in-plane of the structure, the chord tubes were adopted with thin-wall tubes 1,150 mm in diameter and 12 mm to 16 mm thick. The spacing between upper and lower chords is 3.5 m and that of the vertical member of the plane truss is 5 m. The web members were made of tubes 510 mm in diameter and 10 mm thick. A wind bracing system connects the plane truss ribs together. In order to improve the lateral stability of the structure, the arch ribs are inclined inward with a space between the ribs of 2.70 m at the crown and 17.45 m at the base (Fig. 2).

The common sections of CFST bridges' rib are dumbbell-shape type, space truss type and rigidity skeletons box type as shown in Fig. 3 and Fig. 4. Dumbbell-shape types are usually applied to short-span and middle-span CFST bridges. The top and bottom chords of the section are CFST, which are connected by two pieces of stay plates, making a closed hollow along the rib axis. To prevent the local buckling of the stay plates and enhance the shear stiffness of the section, concrete is filled into the hollow sometimes. Space truss type and rigidity skeletons box type are utilized in the design of long-span CFST bridges.The features of these section types are noted as strong lateral stiffness, high lateral stability and load-carrying capacity. The disadvantages of these two types are listed as follows: numerous truss members and welding seams between them lead to difficult fabrication details. Moreover, due to the

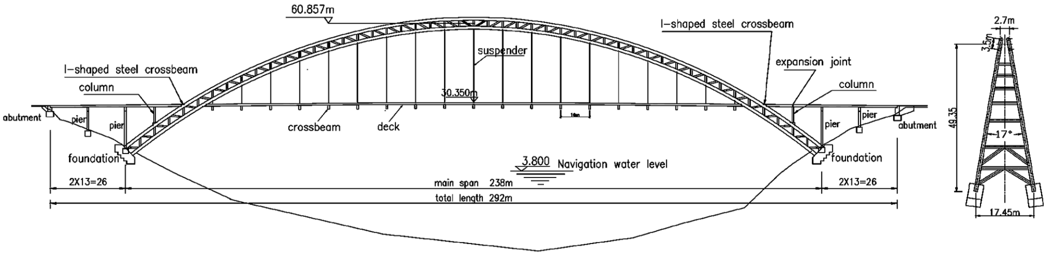


Fig. 2 Elevation view of Tongwamen bridge (dimensions in m)

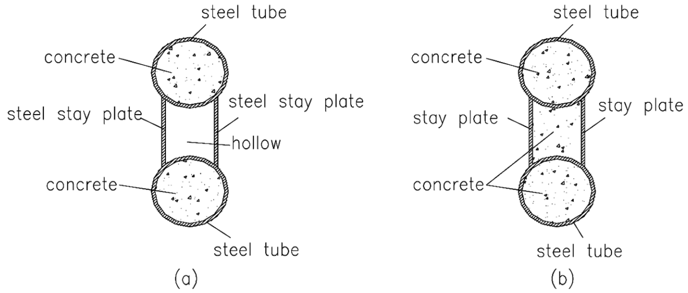


Fig. 3 Dumbbell-shape type section

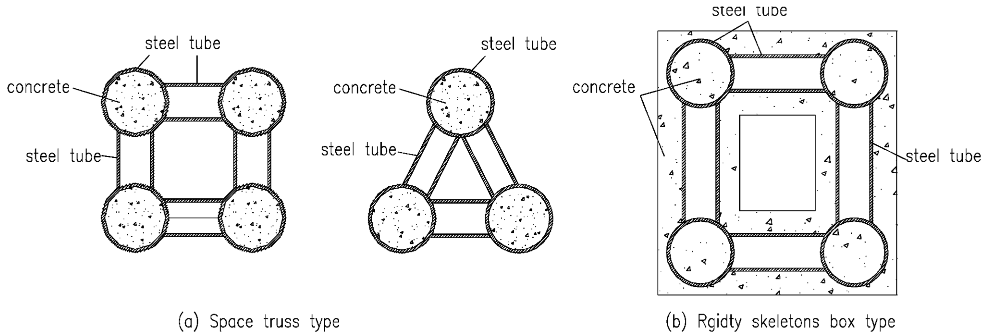


Fig. 4 Space truss type section and rigidity skeletons box type section

transverse width of the ribs are too broad relatively, it would cause the ribs occupying too much effective width of deck or increasing the span of the crossbeams. So they are suitable to wide bridges. Space truss type section would be difficult to manufacture and the numerous members would actually spoil the beauty of the structure. Thus, another new section type, plane truss type section rib, which was made of two CFST chords and web member system, were carried out. This will overcome above shortcomings when adopting space truss type or rigidity skeletons box type. The lateral stiffness of the ribs in the plane truss type is quite low, while, wind power in the Tongwamen channel is quite strong. So the lateral stability of the structure was the critical consideration in design.

Firstly, the lateral stability of the structure was improved by careful design of the lateral braces(Fan 1986, Li 1992). The stability study of designing appropriately the lateral braces was discussed in detail. The calculation and analysis of Tongwamen Bridge indicate the most acceptable design is achieved by adopting plane-truss type lateral braces near the arch crown and K-shaped lateral braces near the arch springing. Moreover, it is very important to set K-shaped lateral braces between the arch ribs at the position of the vertical clearance of vehicular traffic(Zhang *et al.* 2002). Secondly, the stiffness in-plane of the rib could be increased by adjusting the distance of the two top and bottom CFST chords(Deng 2003), and a little steel cost in web system was increased.

Ref.(Zhang *et al.* (2004), Fan (1986), Li (1992), Zhang *et al.* (2002), Deng (2003)) all adopted the deterministic method to research the stability of Tongwamen Bridge. Structural stability reliability analysis has been used widely to assess the uncertainties in many structures such as bridges engineering(Xu *et al.* 2004, Zhang *et al.* 2005). In this paper, the improved response surface method (RSM) was employed to obtain the reliability index of lateral stability.

2. A new strategy for the improved RSM with geometric method

In reliability analysis, the performance of a structure or any other system is governed by a state function of basic random variates (RV). The probability of failure is expressed as the integral of the joint probability density function over the failure domain. Let the random vector be denoted by $X = (X1,X2,...,Xn)$, where n is the number of basic RV, and the joint probability density function is represented by $f_X(x)$; then the failure probability is expressed as

$$P_f = \int_{g(x) \leq 0} f_X(x)dx \tag{1}$$

where the state function $g(x)$ is defined such that $g(x) = 0$ on the limit state surface, $g(x) > 0$ in the safe domain, and $g(x) < 0$ in the failure domain(Zhang *et al.* 2005).

In practice the state function $g(x)$ may be or may not be explicit, and the analytical solution of Eq(1). is in many cases difficult to obtain. Therefore, various methods and algorithms have been proposed to approach the failure probability.

The Monte-Carlo simulation (MCS) method has the superiority for structures where explicit failure functions are not available. The main idea of the MCS method is to simulate the behaviour of a structural system using a random sampling technique with a computer-based analytical or numerical model (e.g., finite element model). Although this method provides the most accurate results, it always requires high computational efforts, especially when the failure probability is less than 10^{-3}(Zhang *et al.* 2003). Stochastic finite element method (SFEM) is another approach to predict the reliability levels of structures that do not have explicit failure functions, but it must reform the program of determinate FEM. So it is difficult to employ a general calculation program of SFEM to describe different forms of randomness at present time.

Of the most widely used approximation methods, the response surface method (RSM) has been used successfully in many areas. The basic idea of the RSM is to approximate the actual state function, which may be implicit and/or very time-consuming to evaluate, whereas the so-called response surface function (RSF) that is easier to deal with. The RSF commonly takes the form of polynomials of the basic RV. After the response surface has been fitted to a sequence of sampling points, the reliability analysis can then be carried out. The crux of the RSM is to achieve a good fit of the RSF to the sampling points, particularly in the neighborhood of the design point(Zhao *et al.* 2000). The RSM is more economical than the MCS method, yet the results obtained are reasonably accurate.

The principle of geometric method is based on the geometric purpose for reliability index β. It utilized the optimization method to find the minimum distance, which just is the value of reliability index β, between the initial point and the boundary of failure domain in standard normal space. The advantage of geometric method is that avoiding the error from the linearization of limit state function while having good efficiency and accuracy.

Because the RSM is employed to estimate the failure surface by an approximate function for a specific region, the calculation is an iterative process step by step. Generally the RSM accesses sample points, which total number is 2n + 1, around an interpolation point. Then the structural analysis of 2n + 1 times are executed to achieve 2n + 1 structural behaviours. Furthermore, the 2n + 1 undetermined coefficients of RSF equation would be obtained. The structural analysis is very time-consuming, particularly for many great complex structures. So it is significant to decrease the quantity of sample point in order to reduce the time of structural analysis when the RSM is adopted to keep good accuracy in reliability analysis.

The traditional RSM, which positioning sample points were selected according to interpolation point, does not always fit the response surface very closely to actual limit state surface. Therefore, in this paper, a improved strategy is adopted, in which the sampling points selected in the initial stage is replaced by interpolation point generated in the iteration process one by one until the convergence conditions are meet(Das and Zheng 2000). For the high grade non-linearity of limit state function, the convergence and computational costs will improve.

3. Reliability Analysis of whole lateral stability

3.1. Calculation model

This paper studies Tongwamen Bridge's reliability analysis for the first-kind of stability in the operation stage. In order to research the random variable of steel tube and concrete infill effecting on stability reliability, the model of arch rib's chord is employed the double-element model. It is to say there are two elements, which are steel tube and concrete element, between the same FEM nodes of arch rib. The space beam elements are adopted in the following members: the chords, web bars, lateral braces of arch rib, the cross and longitudinal deck beam. And cable elements are utilized for suspender members. Because the model is considered the constraint action on the displacement of arch ribs by the suspender and deck, which is the action of the non-orienting force to increase the in-plane and out-of-plane stability in though bridge and half-through bridge, it should simulate really the original structure behavior.

3.2. Checking load case

On the basic of the mean values of the design structural parameters, the ultimate load coefficient for first-kind stability is obtained to find the worst-case load. The possible load cases of the operation stage are listed as the following:

(1) Dead load + wind load
(2) Dead load + wind load + two motor vehicles load on all bridge (off-center) + pedestrian load on all bridge
(3) Dead load + wind load + two motor vehicles load on half span (off-center) + pedestrian load on half span
(4) Dead load + wind load + one motor vehicle load on half side (off-center) + pedestrian load on half side
(5) Dead load + wind load + one motor vehicle load on half span (off-center) + pedestrian load on half span and half side
(6) Dead load + wind load + trailer load on middle span (off-center)
(7) Dead load + wind load + trailer load on 1/4 span (off-center)

The rib chord, web member and deck all bear the wind load. The two motor and one motor vehicle load have off-center distance respectively of 0.55 m and 2.1 m. That of the trailer load is 1.15 m. The off-center load is equivalent to vertical load and torsion moment forcing on the deck element. The calculation result is shown in the following Table 1.

All the buckling modes of seven load cases are out-of-plane buckling. The shape of lateral buckling is

Table 1 Stability coefficient λ of Tongwamen Bridge

Load case	1	2	3	4	5	6	7
Stability coefficient λ	7.168	6.238	6.565	6.777	6.798	6.936	7.057

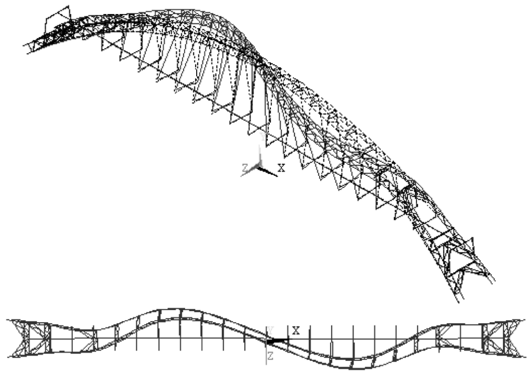


Fig. 5 Buckling shape of first-order

two antisymmetric half-waves indicated in Fig. 5. Even under the worst load case, the stability coefficient is greater than 4~5, which is the meet of the code. Form the Table 1, we can see that the worst-case load case is the second load case. So the stability reliability should be studied on the basic of this load case.

3.3 Calculation of reliability index

Using the above improved RSM, Tongwamen Bridge's stability reliability is assessed. Due to the incline inward degree is an important parameter, the arch rib model is created in the local coordinate system. When the degree of local coordinate system is adjusted, the incline inward degree of arch rib is changed simultaneously. Thus the incline inward degree is regarded as a RV. In this paper, the following parameters are assumed as the RV: Young's modulus Ei of arch rib, lateral braces, suspender and deck; section areas Ai; bulk density ri; axle weight of vehicle load-20; incline inward degree. Because it has not the specific statistic analysis on the material and physical dimension for the arch rib and suspender in Li and Zhang (2007), the distribution types are presumed as listed: Young's modulus, bulk density and incline inward degree belong to normal; section areas defer to log-normal; loads subject to Maximum value I. The properties of RV are shown in Table 2.

Taken account of the randomness for structure and load, the criterion is formulated as an implicit limit state function as

$$g(X) = \lambda(X) - 4.0 \tag{2}$$

Where X denotes the random vector and the properties of RV are indicated in Table 2. All variables are assumed to be uncorrelated. Here $\lambda(X)$ represents the actual first-order factor of lateral buckling as a function of all basic variables, the limit state is defined as the exceedance of the safe factor of lateral stability for arch bridge.

Then the improved RSM is employed, the reliability index for lateral stability is achieved $\beta = 5.0603$ and the failure probability P_f is 2.09329e-7. The whole calculation process executed five steps of iteration.

4. Sensitivity analysis of reliability index

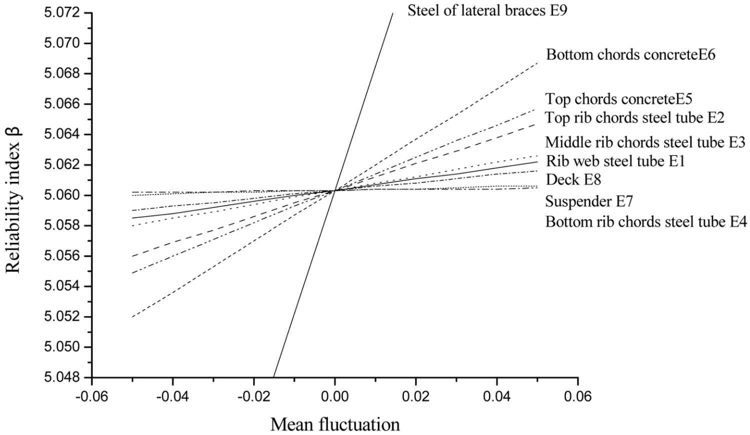
The influence factor of Tongwamen Bridge's stability was discussed detailedly in Deng (2003), Pan

Table 2 The properties of the random variables

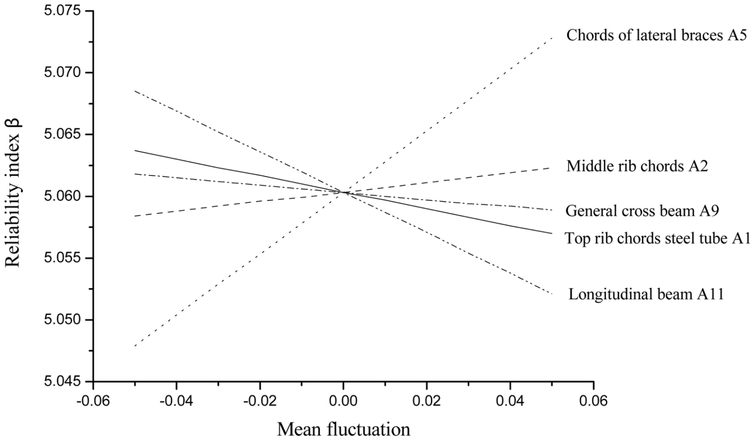
Random variables		Position	Mean value	Standard deviation	Distribution type
Young's modulus	E_1 / Kpa	Rib web steel tube	210e6	0.1	Normal
	E_2 / Kpa	Top rib chords steel tube	210e6	0.1	Normal
	E_3 / Kpa	Middle rib chords steel tube	210e6	0.1	Normal
	E_4 / Kpa	Bottom rib chords steel tube	210e6	0.1	Normal
	E_5 / Kpa	Top chords concrete	35e6	0.1	Normal
	E_6 / Kpa	Bottom chords concrete	35e6	0.1	Normal
	E_7 / Kpa	Suspender	195e6	0.1	Normal
	E_8 / Kpa	Cross and longitudinal beam of deck	30e6	0.1	Normal
	E_9 / Kpa	Lateral braces steel tube	210e6	0.1	Normal
Areas	A_1 / m^2	Top rib chords steel tube	0.0429	0.05	Log-normal
	A_2 / m^2	Middle rib chords steel tube	0.0499	0.05	Log-normal
	A_3 / m^2	Bottom rib chords steel tube	0.0570	0.05	Log-normal
	A_4 / m^2	Rib web	0.01571	0.05	Log-normal
	A_5 / m^2	Chords of lateral braces	0.028	0.05	Log-normal
	A_6 / m^2	Webs of lateral braces	0.00885	0.05	Log-normal
	A_7 / m^2	Chords of K-shaped braces	0.0188	0.05	Log-normal
	A_8 / m^2	Steel cross beam	0.0472	0.05	Log-normal
	A_9 / m^2	General cross beam	0.62	0.05	Log-normal
	A_{10} / m^2	Suspender	0.001424	0.05	Log-normal
	A_{11} / m^2	Longitudinal beam	4.063	0.05	Log-normal
	A_{12} / m^2	Bar stay	0.2043	0.05	Log-normal
Incline inward degree	Degree	Arch rib	8.5	0.05	Normal
Bulk density	r_1 / $kN.m^{-3}$	Top rib chords steel tube	78.5	0.05	Normal
	r_2 / $kN.m^{-3}$	Middle rib chords steel tube	78.5	0.05	Normal
	r_3 / $kN.m^{-3}$	Bottom rib chords steel tube	78.5	0.05	Normal
	r_4 / $kN.m^{-3}$	Top chords concrete	25	0.05	Normal
	r_5 / $kN.m^{-3}$	Bottom chords concrete	25	0.05	Normal
	r_6 / $kN.m^{-3}$	Deck	25	0.05	Normal
Loads	P_1 / kN	Fore axle of main vehicle	182	0.1	Maximum value I
	P_2 / kN	Rear axle of main vehicle	338	0.1	Maximum value I
	P_3 / kN	Fore axle of heavy loading vehicle	312	0.1	Maximum value I
	P_4 / kN	Centre axle of heavy loading vehicle	312	0.1	Maximum value I
	P_5 / kN	Rear axle of heavy loading vehicle	156	0.1	Maximum value I
	P_6 / (kN/m)	Pedestrian load	6	0.1	Maximum value I

(2004). Through sensitivity analysis for the mean and variability coefficient, the major factors can also be found in the reliability research. The reliability index varies with the mean and variability coefficient of Young's modulus, areas, bulk density, and other factors are shown in Fig. 6 and Fig. 7.

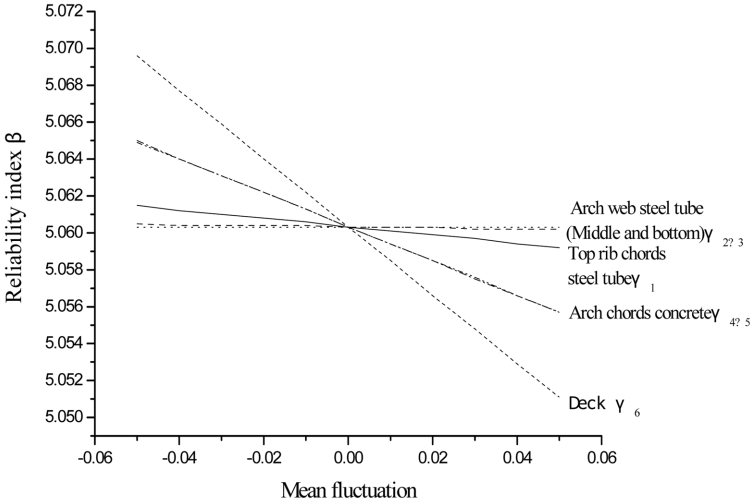
From the RV importance of sensitivity analysis for reliability index, we can see that:



(a) Young's modulus effect

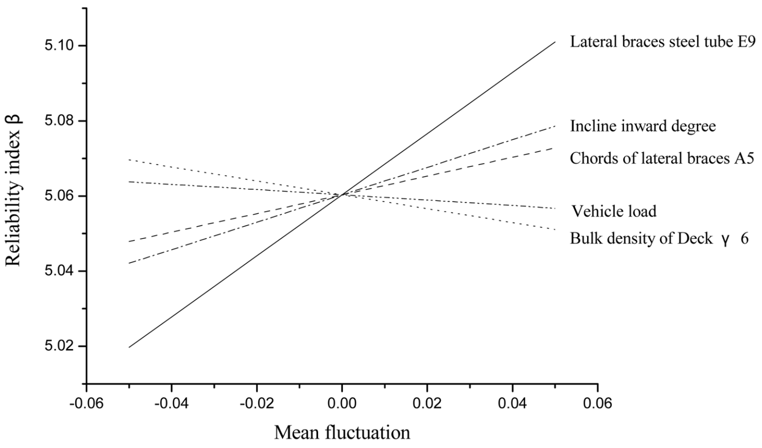


(b) Section area effect



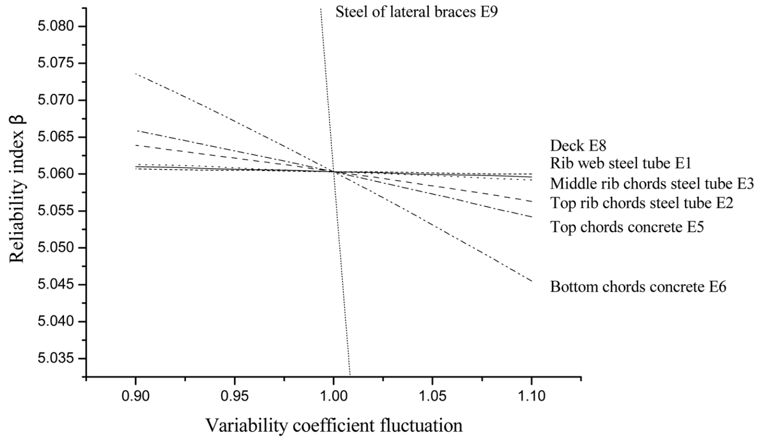
(c) Bulk density effect

Fig. 6 The mean value of random variables effect on reliability index

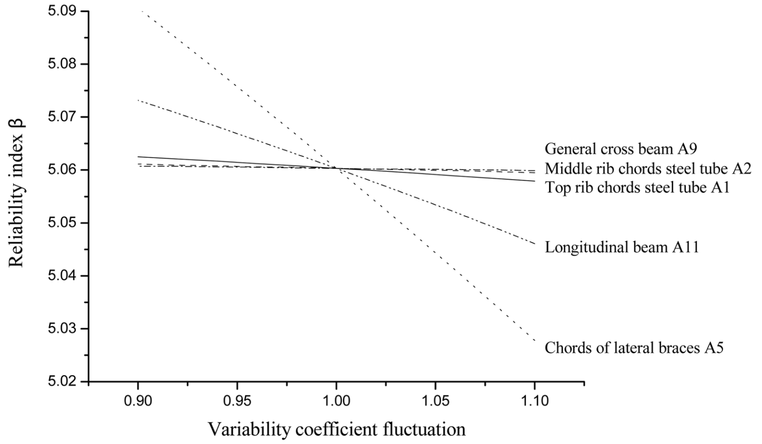


(d) Major factors effect

Fig. 6 Continued

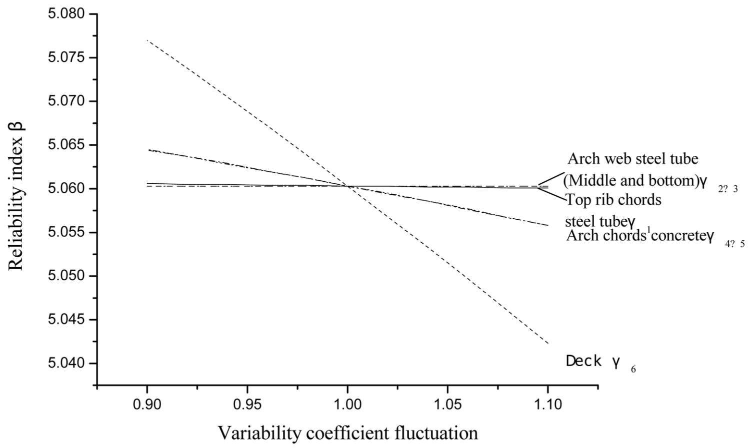


(a) Young's modulus effect

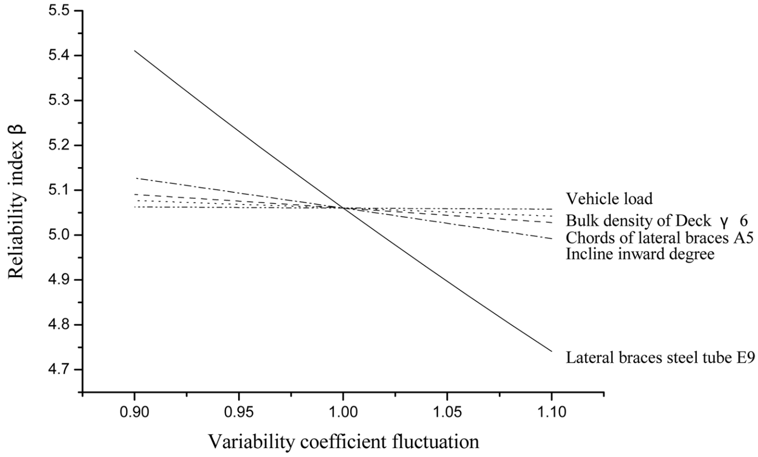


(b) Section area effect

Fig. 7 The variation coefficient of random variables effect on reliability index



(c) Bulk density effect



(d) Major factors effect

Fig. 7 Continued

① The effect of Young's modulus of lateral braces steel tube is greatest, and that of the bottom chords, concrete, top chords concrete and top rib chords steel tube is greater. The Middle rib chords steel tube, rib web steel tube, longitudinal and cross beam of deck have little effect. However, the suspender and bottom rib chords steel tube have no effect. The structural reliability increases with the rising of mean value.

② The effect of lateral brace chords' area is greatest, and that of longitudinal beam; top rib chords steel tube, middle rib chords steel tube and general cross beam is greater; while the other factors have no effect. Reliability index increases with the rising of mean value for lateral brace chords and middle rib chords. But it decreases with that of longitudinal beam, top rib chords and general cross beam.

③ The effect of deck bulk density is greatest, then that of the rib concrete and top rib chords steel tube is greater. Because the increasing of the bulk density leads to the growing of dead load, the structural reliability is reduced. The bulk densities of middle and bottom rib chords have no effect.

④ Increasing the mean value of lateral braces stiff and inclining inward degree can enhance obviously the reliability of lateral stability. These two factors are same major parameters in variation coefficients. The bulk density deck and vehicle load are secondary factors. The variation coefficient of RV would lead to the decreasing of structural reliability.

5. Conclusions

The structure type and the layout of lateral braces between the ribs of arch are very important in terms of the lateral stability, especially in the case of a large span, narrow arch bridge. Tongwamen Bridge is a CFST bridge of 238m span, yielding deck width to span ratio of 1/23.8. It adopted audaciously the plane truss type section rib. The proper later braces and incline inward degree were designed carefully to ensure the stability. Tongwamen Bridge is the longest span bridge of plane truss type CFST arch bridge in China.

In this paper, a new strategy for positioning sampling points of the response surface method (RSM), based on the composite method combining RSM with geometric method for structural reliability analysis, is employed to obtain the reliability index of lateral stability. In addition the correlated parameters were discussed in detail to find the major factors. According to the analysis results, increasing the stiff of lateral braces between the arch ribs and setting the proper inward-incline degree of the arch rib can enhance obviously the reliability of lateral stability. Moreover, the influence of deck action of non-orienting force is less than the two factors above. The effect of Young's modulus of bottom chords concrete is greater than the top chords concrete, so the quality of bottom chords concrete should be controlled strictly during construction. The arch ribs are proved to be safe enough to keep excellent stability. The calculated result provides the foundation that the plane truss rib would be a competitive solution for a long-span, narrow, CFST arch bridge.

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