Tomorrow's Challenge in Bridge Span Length

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Summary

The potential requirement of extreme bridge spans is firstly discussed according to horizontal clearances for navigation and economical construction of deep-water foundation. To ensure the technological feasibility of suspension bridges with longer spans, the static estimation of feasible span length is then made based on current material strength and weight of cables and deck. After the performances of the countermeasures for raising the aerodynamic stability are reviewed, a trial design of a 5,000 m suspension bridge, which is estimated as a reasonable limitation of span length, is finally conducted to respond to the tomorrow's challenge in span length of suspension bridges with the particular aspects, including dynamic stiffness, aerodynamic flutter and aerostatic stability.

Keywords: Suspension bridge; span length; potential requirement; technological feasibility; aerodynamic limitation.

1. Introduction

As a human dream and an engineering challenge, the structural engineering of bridging larger obstacles has entered into a new era of crossing wider sea straits, for example, Messina Strait in Italy, Qiongzhou Strait in China, Tsugaru Strait in Japan, and Gibraltar Strait linking European and African Continents [1]. One of the most interesting tomorrow's challenges has been identified as bridge span length limitation, in particular the span limits of suspension bridges as a bridge type with potential longest span. The construction of long-span suspension bridges has experienced a considerable development for about one century. It took about 54 years that span length of suspension bridges grew from 483 m in Brooklyn Bridge to 1,280 m in Golden Gate Bridge in 1937, and had an increase by a factor of about 2.7. Although the further increase in the next 61 years from Golden Gate Bridge to Akashi Kaikyo Bridge in 1998 was only 1.6, another increase factor about 1.6 will be realized in Messina Strait Bridge with a 3,300 m main span within 12 years in 2010.

The dominant concerns of super long-span bridges to bridge designers are basically potential requirement, technological feasibility and dynamic and aerodynamic considerations. The potential requirement of extreme bridge spans is basically related to horizontal clearances for navigation and economical construction of deep-water foundation. Based on current strength and weight of cables and deck of materials, for example, steel, glass fiber reinforced plastics (GFRP) and carbon fiber reinforced plastics (CFRP), the static estimation of feasible span length can be made to ensure the technological feasibility of suspension bridges with longest spans. After the performances of countermeasures for raising the aerodynamic stability are reviewed, including cable system modification, slotted deck solution, additional stabilizers and passive and active control, a trial design of a 5,000 m suspension bridge, which is estimated as a reasonable limitation of span length, is finally conducted to respond to the tomorrow's challenge in span length of suspension bridges based on dynamic characteristics, aerodynamic flutter stability and aerostatic torsional performance [2].

2. Potential Requirements of Bridge Span

Bridging wider sea strait requires longer bridge span based on not only ever-growing navigation requirements but also very deep water. It is well known that the horizontal clearances have been increased greatly to accommodate huge size marine vessels in recent years. The intense competition among harbor cities has lead to ultra long-span bridges provided for wider and higher navigation clearance in order to obtain more benefit from ocean shipping business. Another reason for building super span bridges is in the concern for ship collision with bridge substructures. Besides the safety issue and potential loss of lives resulted from ship collision, there are a number of related economic impacts.

It is required by navigation to minimize or eliminate piers in the waterway considered. According to the development trends of large vessels in Table 1, however, there still exists a limit of dead weight tons (DWT) of vessels in order to meet economical transportation provisions including the navigation clearances of existing harbor bridges and the appropriate draught depth of navigable channels for most harbor cities all over the world. It can be predicted that the DWT of the maximum vessel could be about 500,000 t in the future, and the corresponding horizontal navigation clearance should be about 1,600 m. From the viewpoint of safe navigation, therefore, 3,200 m span length should be wide enough for two waterways of 500,000 DWT vessels.

Table 1 *Navigation clearance*

DWT	Ship Length	Navigation Clearance		Draught Depth
(t)	(m)	Height (m)	Width (m)	(m)
35,000	195	34	620	11
50,000	275	46	880	12.5
100,000	300	57	960	15
200,000	320	62	1020	17.5
300,000	340	67	1090	21
500,000*	500	80	1600	25

On the other hand, the longer spans are also required to avoid the construction of deep-water foundation at unpredictable costs. At the narrowest point of Gibraltar Strait, for example, the water is about 480 m deep, and the construction of deep water foundation is much more expensive and time-consuming so that the cost of superstructures and deep water foundations should be balanced economically [3]. However, the water depths of most sea straits in the world are less than 150 m, with the progress in the technology of deep water foundation, the optimal and economic solution of span length can be predicted in the range of 2,000 m to 5,000 m. The potential requirement of bridge spans could be estimated as about 5,000m. The optimal and economic solution of span length in the range of 2,000 m to 5,000 m will depend on the cost of deep-water foundation in designing the multi-span suspension bridge for sea straits crossing.

3. Technological Feasibility of Span Length

To ensure the technological feasibility of suspension bridges with longest spans, it is interesting to cope with static estimation based on material strength and weight of cables. For the center span of a typical three-span suspension bridge, by assuming the main cable shape to be parabolic, the feasible span length L can be expressed by the following inequality [4]

$$L \le \frac{8nA\sigma_a / w_c}{\sqrt{1+16n^2}\left(1+w_s/w_c\right)} \tag{1}$$

in which, n – ratio of cable sag to span;

σ_a – allowable stress of cables, and $\sigma_a \cong 0.5\sigma_u$ (σ_u = ultimate stress);

A – cable area of wires;

w_c – cable weight per unit length, and $w_c \cong 1.1A\gamma_c$ (γ_c = material density);

w_s – deck weight per unit length including dead weight and live loads of traffic.

If the weight ratio ws/wc approached to zero, the ultimate span length L_∞ could be approximately obtained with the cable materials including high strength steel, GFRP and CFRP under the conventional sag-span ratios of 1/8 and 1/11 as follows

$$L_\infty = \frac{4n\lambda}{\sqrt{1+16n^2}} \cong \begin{cases} \dfrac{80{,}000n}{\sqrt{1+16n^2}} \ (Steel) \cong \begin{cases} 8900m & (n=1/8) \\ 6800m & (n=1/11) \end{cases} \\ \dfrac{100{,}000n}{\sqrt{1+16n^2}} \ (GFRP) \cong \begin{cases} 11100m & (n=1/8) \\ 8500m & (n=1/11) \end{cases} \\ \dfrac{240{,}000n}{\sqrt{1+16n^2}} \ (CFRP) \cong \begin{cases} 26700m & (n=1/8) \\ 20400m & (n=1/11) \end{cases} \end{cases} \tag{2}$$

in which, λ is the ratio of ultimate stress σ_u to equivalent density $1.1\gamma_c$, and the values of λ are about 20,000 m, 25,000 m and 60,000 m for steel, GFRP and CFRP, respectively.

Equation (1) can be simplified as

$$L \le \frac{L_\infty}{1+w_s/w_c} \tag{3}$$

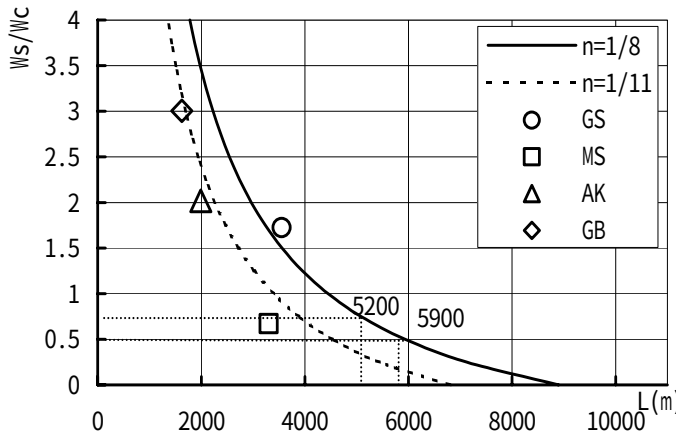


Fig. 1 *Span length versus weight ratio*

With the application of steel cables, the relationship between span length L and weight ratio w_s/w_c, Equation (3), can be plotted as Figure 1, in which additional four dots represent four bridges or bridge schemes including Great Belt (GB), Akashi Kaikyo (AK), Messina Bridge (MS) and Gibraltar Bridge (GS). In order to follow the requirement of Equation (3), the bridge span and weight ratio should be kept in the area of the lower left of the appropriate curve corresponding to the sag-span ratio. If the weight ratios of w_s/w_c = 0.7 like Messina Strait Bridge and even w_s/w_c = 0.5 are designed, the span length can be enlarged up to 5,200 m and 5,900 m, respectively.

4. Aerodynamic Countermeasures of Suspension Bridges

In the design of long-span suspension bridge, one of the most challenging problems is the aeroelastic stability at the design wind speed. As an example, the design speed of 60 m/s was assumed for Great Belt Bridge with a span length of 1,624 m, while the value of 78 m/s was defined for Akashi Kaikyo Bridge with a 1,991 m main span. The experience gained from these two recently built world-record span bridges, together with the parametric analysis considered in the preliminary study of the Gibraltar strait project [5], revealed that the span length of 2,000 m should be its intrinsic limit in the aspect of aerodynamic stability for the classic suspension bridges [6][7]. In other words, some countermeasures should be adopted to increase the aerodynamic stability for suspension bridges with the spans beyond 2,000 m, for example, 3,200 m or 5,000 m, which is potentially required by navigation clearance or under the condition of extreme water depths, and is technically confirmed based on static estimation.

4.1 Cable system modifications

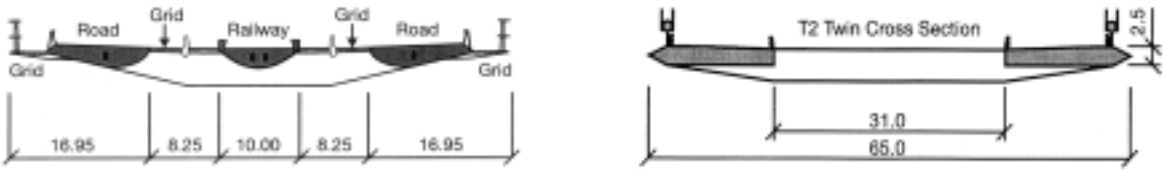
One of the most important reasons, which the traditional suspension bridges with single box girders seem to stop at the span limitation of 2,000 m, is the higher trend of reduction of the torsional stiffness versus span length, which consequently leads to a decrease of fundamental torsional frequency [6]. In order to increase torsional stiffness of suspension bridges with main spans about 3,000 m, some researches have proposed a couple of structural modification methods, in particular cable system modifications, which can be concluded into three types as follows.

(a) Crossed hanger system [7] or combination of vertical and horizontal cross stays [8]
(b) Mono [7] or spatial [4] cable systems

(c) Three or four cable systems [7]

4.2 Slotted deck solutions

A parallel approach to the aeroelastic stability problem is an attempt to reduce the aerodynamic forces based on the configuration improvement of cross sections of bridge decks [9]. With adopting a triple-girder deck with a total width of 60 m shown in Figure 2a, Messina Strait Bridge has a main span of 3,300 m and a critical wind speed of 80 m/s [10]. In the design competition of the Gibraltar Strait Crossing Project, the suspension bridge schemes with multiple super long spans have been adopted with the twin-box girder in Figure 2b, whose critical wind speeds are 76 m/s and 67 m/s for the 3,550 m and 5,000 m spans, respectively [5].



(a) *Triple girder deck of MS* (b) *Twin box girder of GS*

Fig. 2 *Slotted deck configurations*

4.3 Vertical and horizontal stabilizers

Some Japanese scholars have investigated additional devices on decks called vertical stabilizers (central barriers) and horizontal stabilizers (guide vanes) for further improvement of aerodynamic stability of suspension bridges with slotted decks. As an example of the preliminary study, the objected suspension bridge with a 2,500 m span was tested and compared with the slotted deck, the vertical stabilizer only (Figure 3a) and both the vertical and horizontal stabilizers (Figure 3b). Through the sectional model test, it was found that the critical wind speeds could be reached to 62 m/s for the slotted deck with the vertical stabilizer, which has an increase about 35% for the same slotted deck without the vertical stabilizer, and to 82.5 m/s for the slotted deck with both the vertical and horizontal stabilizers, a further increase about 33% [11]. Another research result also confirmed the critical wind speed enhancement about 38% for using both the vertical and horizontal stabilizers in the trial design of a suspension bridge with a span length of 3,000 m [12].

(a) *With vertical stabilizer only* (b) *With vertical and horizontal stabilizers*

Fig. 3 *Slotted deck with vertical and horizontal stabilizers*

4.4 Passive and active control

As far as concern of possible methods for raising total amount of damping, in particular aerodynamic damping, several passive and active control methods have been proposed [13]. Most of passive aerodynamic dampers consist in wing profiles fixed at the section leading or trailing edge to add torsional and vertical damping, as well as the cross terms. Active control devices have never been applied in real structures, but already considered by several researches in a feasibility stage [14].

4.5 Trial design scheme with countermeasures

As a sample bridge, a typical three-span suspension bridge with a 5,000 m central span and two 1,600 m side spans is considered and shown in Figure 4. In order to improve aerodynamic stability limit, two kinds of generic deck sections, widely slotted deck (WS) without any stabilizers in Figure 5a and narrowly slotted deck with vertical and horizontal stabilizers (NS) in Figure 5b, were investigated. The NS cross section has a total deck width of 50 m for the 5,000 m spanned suspension bridge while the WS provides a wider deck solution of 80 m [2].

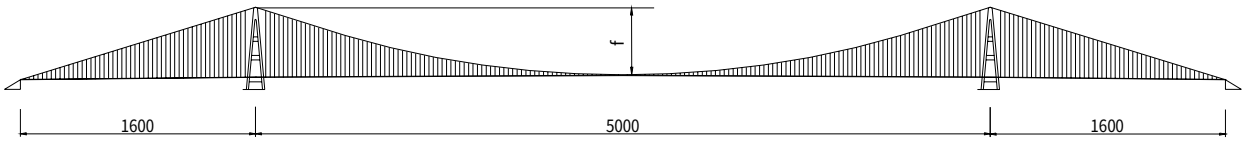
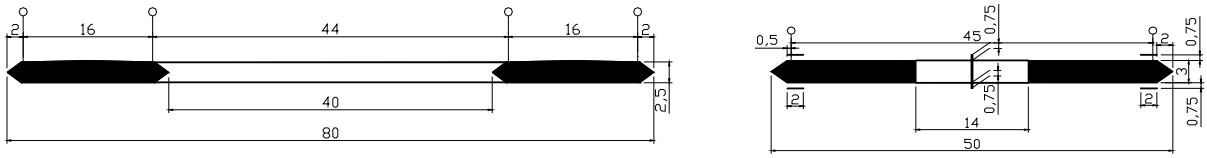


Fig. 4 *Suspension bridge scheme with a 5,000 m central span*



(a) *WS Cross section* (b) *NS Cross section*

Fig. 5 *Geometry of deck sections of WS and NS*

5. Dynamic Stiffness of Bridge Scheme

An analytical examination was attempted to find out the dynamic characteristics of a suspension bridge with super long spans. For super long-span suspension bridges, the most important dynamic characteristic is the overall dynamic stiffness, provided with main cables as well as stiffening girder and two pylons. The dynamic stiffness analysis of main cables, stiffening girder and pylons is carried out for four sag-span ratios of 1/8 to 1/11 combined with the two above-mentioned deck configurations of WS and NS.

5.1 Stiffness of main cables

A significant part of the dynamic stiffness in vertical bending and torsion is provided by the main cables, although the overall stiffness of a suspension bridge is generally contributed by main cables, girder and pylons [15]. In fact, the vertical bending motion and the torsional motion of the deck are, as far as the cable motion is concerned, the matter of in-phase and out-of-phase activities between two main cables. For the FEM dynamic analysis, the stiffness term of cable elements consists of two components, elastic stiffness directly related to cable area, and geometric stiffness provided by non-linearity effects of the elastic stiffness. As a result, the stiffness of main cables basically depends upon the area of cables. In order to select an appropriate value of cable area, the minimum cable area according to static requirement can be firstly calculated by assuming $w_s = w_{sd} + w_{sl} = 240 + 42 = 282$ kN/m and $\gamma_c = 78.5$ kN/m^3 in Equation (3)

$$A \geq \frac{w_s}{\eta\gamma}\frac{L}{L_\infty - L} = \frac{3.124L}{L_\infty - L} \tag{4}$$

According to Equation (4), the minimum values of cable areas are approximately 4.01 m^2 for n = 1/8, 5.04 m^2 for n = 1/9, 6.51 m^2 for n = 1/10 and 8.68 m^2 for n = 1/11, respectively. Dynamic characteristics of a suspension bridge is not only related to the cable stiffness but also the cable mass and its moment of inertia. Through a series of the parametric analysis of cable stiffness and mass system, it is interesting to learn that the difference of the corresponding natural frequency between the minimum cable area and a double one is no more than 5% for all four sag-span ratios with the two deck configurations. The reason for this can be attributed to the increase of cable mass with the increase of the cable stiffness, which is counteracted by cable mass accordingly. As far as the dynamic characteristic is concerned, therefore, the minimum values of cable areas for all four ratios n is utilized in the following study.

5.2 Stiffening girder contribution

The contribution of the stiffening girder to the overall stiffness is greater in torsion than in bending for traditional suspension bridges [15]. It was reported by Brancaleoni that the deck contribution to the global stiffness in the case of the Great Belt is about 30% and 60% for the fundamental vertical bending and torsional modes, respectively [16]. These values seem to remain at the same order of magnitude in the case of the Akashi Kaikyo. The deck contribution, however, is believed to be much less in a suspension bridge with a 5,000 m main span, since the deck stiffness and mass are in

small proportion to the cable ones. This is absolutely true in both WS and NS deck configurations shown in Table 2.

Table 2 *Stiffness contribution of stiffening girder*

Ratio	Lateral Stiffness (%)		Vertical Stiffness (%)		Torsional Stiffness (%)	
	WS	NS	WS	NS	WS	NS
n = 1/8	4.4	4.9	0.2	0.3	14.2	29.3
n = 1/9	4.3	4.8	0.2	0.3	11.4	24.5
n = 1/10	4.3	4.8	0.2	0.2	8.9	18.5
n = 1/11	4.3	4.7	0.2	0.2	6.4	13.9

5.3 Stiffness influence of pylons

Though the pylon stiffness does influence the overall stiffness of a traditional suspension bridge, the extent of it does not change too much in the super long-span case, except for the geometric stiffness of pylon elements. The stiffness difference between the proposed pylons and the pylons with infinite rigidity in the bridge are shown in Table 3. Apart from the vertical bending stiffness, the influence of the variation of pylon stiffness selection can be ignored in the dynamic analysis.

Table 3 *Relative stiffness of the pylons*

Ratio	Lateral Stiffness (%)		Vertical Stiffness (%)		Torsional Stiffness (%)	
	WS	NS	WS	NS	WS	NS
n = 1/8	0.9	1.3	10.2	9.8	1.2	1.0
n = 1/9	1.1	1.4	13.4	12.6	1.8	1.2
n = 1/10	1.6	1.8	17.6	16.9	2.5	1.3
n = 1/11	2.1	2.1	22.4	20.7	3.2	1.3

6. Aerodynamic and Aerostatic Performance

Suspension bridges with very long spans are characterized by varying dynamic mode shapes along the bridge span when excited to vibrate. This mode shape effect is usually accounted for by using generalized properties of section inertia and aerodynamic loading described by flutter derivatives in the aerodynamic stability analysis, which can be performed by the multi-mode or full-mode participation methods [17]. The aerostatic effect on bridge structures is usually treated as an action of three aerostatic components of wind forces, and these components can be described as a function of the effective angle, the torsional deformation of a deck, which usually changes along the longitudinal axis of a bridge. The aerostatic torsional divergence analysis can be carried out with iteration approach of aerostatic force and structural elastic resistance [18].

6.1 Natural frequency computation

The finite-element idealization of the bridge was attempted with the finite beam elements for the longitudinal girder and the pylons, and the cable elements considering geometric stiffness for the main cables and hangers, the geometric dimensions and material properties for these elements were provided and result in the most important computational parameters listed in Table 4.

Table 4 *Parameters of stiffness and mass*

Section	Main Cables			Stiffening Girder			
	EA (Nm^2)	m (kg/m)	I_m (kgm^2/m)	EI_y(Nm^2)	GI_d(Nm^2)	m (kg/m)	I_m(kgm^2/m)
WS	$0.61\sim1.12\times10^6$	$2.62\sim4.82\times10^4$	$2.36\sim4.33\times10^7$	4.7×10^{11}	2.8×10^{11}	24000	2.16×10^7
NS	$0.61\sim1.12\times10^6$	$2.62\sim4.82\times10^4$	$1.27\sim2.33\times10^7$	8.1×10^{11}	4.1×10^{11}	24000	5.40×10^6

Having performed a dynamic finite-element analysis, the first several natural frequencies of the structures have been extracted for all four ratios n and the two deck configurations in Table 5. The fundamental lateral bending frequencies vary about 16% for the WS section and 17% for the NS section from n =1/8 to n =1/11, but almost keep in the same value between the WS and NS deck configurations. The fundamental vertical bending frequencies are not influenced significantly by both deck configurations and the sag-span ratios. The variation of the fundamental torsional frequencies follow different ways with the ratio n in the two deck configurations, in which the

frequency values go up in the WS section and go down in the NS section with the decrease of the ratio *n*, but it is interesting to see that the frequency ratio of torsion to vertical bending monotonically decrease with the reduction of the ratio *n*.

Table 5 *Fundamental natural frequencies*

Ratio	Lateral Frequency (Hz)		Vertical Frequency(Hz)		Torsion Frequency (Hz)		Frequency Ratio	
	WS	NS	WS	NS	WS	NS	WS	NS
n = 1/8	0.02199	0.02156	0.05955	0.05936	0.07090	0.09073	1.191	1.528
n = 1/9	0.02322	0.02285	0.06126	0.06115	0.07207	0.08928	1.176	1.460
n = 1/10	0.02438	0.02406	0.06219	0.06204	0.07268	0.08653	1.168	1.395
n = 1/11	0.02548	0.02520	0.06237	0.06219	0.07269	0.08403	1.165	1.351

6.2 Aerodynamic stability analysis

With the dynamic characteristics given in the previous section and numerically obtained flutter derivatives, the critical wind speeds of the suspension bridge were calculated by multi-mode flutter analysis assuming a structural damping of 0.5% relative to critical [17]. The analysis results of critical wind speeds together with the generalized mass and mass moment of inertia are summarized in Table 6. In the case of both sections the critical wind speed increases with the decrease of the ratio *n*, although the frequency ratio of torsion to vertical bending slightly decreases. The most important reason is because of the considerable increase of the generalized properties in the aerodynamic stability analysis. The minimum critical wind speeds for the WS and NS sections are 82.9 m/s and 74.7 m/s, respectively, whose figures are very similar to the aerodynamic limits in the Messina Strait and the Gibraltar Strait.

Table 6 *Critical flutter wind speeds*

Ratio	m ($\times 10^4$kg/m)		I_m ($\times 10^7$kgm^2/m)		f_h (Hz)		f_α (Hz)		U_{cr} (m/s)	
	WS	NS	WS	NS	WS	NS	WS	NS	WS	NS
n = 1/8	6.01	6.79	5.28	2.37	0.05955	0.05936	0.07090	0.09073	82.9	74.7
n = 1/9	6.27	7.43	5.36	3.22	0.06126	0.06115	0.07207	0.08928	88.8	77.4
n = 1/10	6.73	8.33	5.92	3.29	0.06219	0.06204	0.07268	0.08653	90.9	78.9
n = 1/11	7.66	9.52	6.77	3.62	0.06237	0.06219	0.07269	0.08403	98.9	82.7

6.3 Aerostatic stability calculation

After conducted the iteration approach in aerostatic stability calculation [18], the critical wind speeds due to aerostatic torsional stability for the WS deck section are 90 m/s for the ratio of n = 1/8, and 110 m/s for n = 1/11, respectively, while the values for the NS deck section are 120 m/s for the ratio of n = 1/8, and 135 m/s for n = 1/11, respectively. The main reason for wind-induced torsional divergence of the suspension bridge is due to the nonlinear deck deformation under the static wind loading, whose direction and magnitude change with the effective angles of attack.

Having made the comparison and contrast of aerodynamic and aerostatic stability limits, it is very important to conclude that the magnitude of the critical wind speed due to torsional divergence is almost at the same order of the critical flutter speed, in particular for the wider deck configuration, the WS cross section, so that aerodynamic and aerostatic stability limits should be kept at the same importance in the design of super long-span suspension bridges.

7. Conclusions

The potential requirement of bridge spans based on navigation development and deep water sea-straits might be economically limited at a upper bound span of 5,000 m, and the current state-of-the-art technology seems to promise a span length beyond 5,000 m for suspension bridges in the near future. It means that the 5,000 m span length of a suspension bridge could be a reasonable limitation due to either technological or navigable considerations.

The trial design began with the discussion and selection of the overall stiffness of the suspension bridge, which is generally provided by the main cables, the girder and the pylons. A series of dynamic finite-element analysis was then performed to obtain the first several natural frequencies of the structure with different four sag-span ratios and two deck configurations. The key emphasis of this study was placed on the flutter prediction and the torsional divergence analysis, which resulted

in some new findings about aerodynamic stability limits as well as aerostatic stability limits for 5,000 m suspension bridges.

After made the aerodynamic design, analysis and comparison, it can be finally concluded that either an enough-widely slotted deck or a narrowly slotted deck with central and horizontal stabilizers could provide a 5,000 m span-length suspension bridge with high enough critical wind speeds, due to both flutter vibration and torsional divergence, which can meet the aerodynamic requirement from most typhoon-prone areas in the world.

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