Bridge Structures 8 (2012) 25–33
DOI:10.3233/BRS-2012-0035
IOS Press

Characteristics of hanger for a long span suspension bridge

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Abstract. For a suspension bridge, the balance of design, fabrication, and erection of the hangers presents a major concern. The hangers play an important role for the bridge geometry and are very sensitive to length error. This paper focuses on the characteristics of suspension bridge hangers through a study of numerical analyses. Difference between bridges with one hanger rope at a hanger location per each cable plane and with two or more hanger ropes in the longitudinal direction are studied in detail. Erroneous fabrication of angers may cause undesirable results for a real bridge because two or more hangers in the longitudinal direction at one hanger location are occasionally modeled as one hanger element in the design. This simplification may not represent the actual behavior of hangers on suspension bridges. The findings of this study provide important clues to the fabrication requirements of hangers for suspension bridges.

Keywords: Suspension bridge, hanger, imperfection sensitivity

1. Introduction

Several suspension bridge projects with a main span longer than 2,000 m; such as the Messina Strait Bridge in Italy, are currently under planning. Typical details from past experience in the design, fabrication and erection of major structural elements may not be suitable for a longer span suspension bridge. The objective of this paper is to examine the characteristics of hangers for longer span suspension bridges. In the past decades, the use of pin-ended type hanger with parallel wire strand (PWS) dominated over the conventional saddle type due to higher capacity, static wind load, corrosion protection, access to maintenance, and ease of replacement. Therefore this study is focused on PWS hangers, however the application of findings is not limited to PWS hangers.

This paper describes the underlined characteristics of hangers for a longer suspension bridge by using a suspension bridge model with a main span of 3,000 m. First a brief outline on pin-ended hanger is introduced to highlight the conditions that produce the fabrication error. Then, the fundamental characteristics of hangers are overseen by comparing two types of hanger arrangements, i.e. one with one hanger at one hanger location per each cable plan and the other is with two hangers in the longitudinal direction. The former model was likely used for the analysis model even if the planned bridge has two or more hanger ropes in the longitudinal direction. The unbalanced force in a pair of hangers, the static and dynamic wind stability and the imperfection sensitivity for an error of unstressed hanger length are discussed in this paper. The study concludes with proposed criteria for hanger fabrication and erection for longer span suspension bridges.

2. Past experiences

2.1. Akashi Bridge in Japan

In the Akashi Bridge, which is the current longest suspension bridge in the world with main span of 1,990 m, PWS hangers with pin-ended connection both at the clamp and at the deck anchorages are used. This detail is mainly used for easier maintenance and replacement operations [1]. The longest hanger at the tower location is some 200 m between pin centers at the

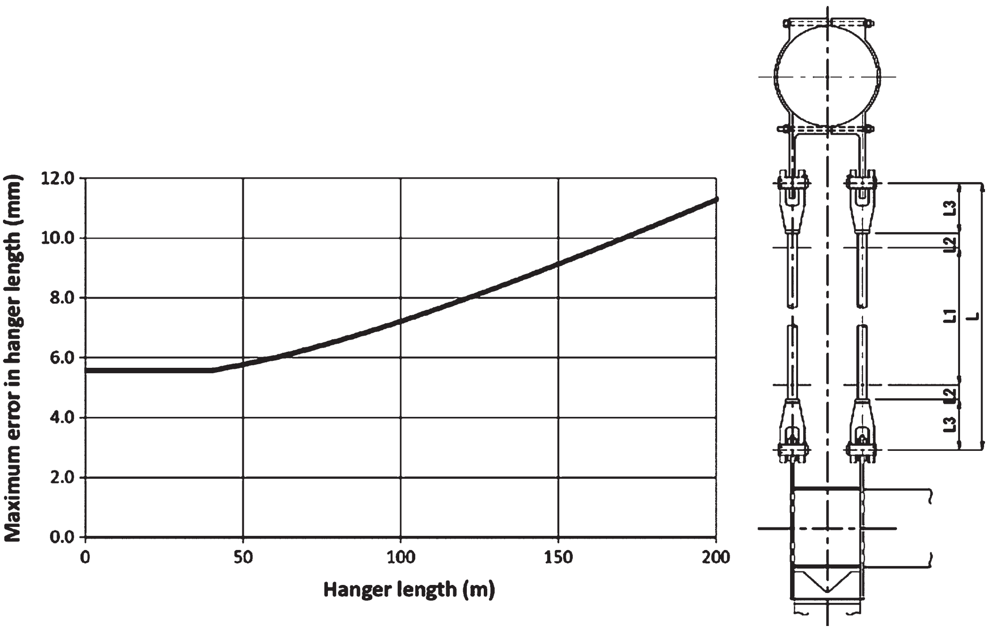

Fig. 1. Maximum manufacturing error of hanger length.

clamp and on the girder. For hangers shorter than 15 m, the conventional saddle type with center fit rope core (CFRC) is adopted. This provides a realistic solution for a large angular deformation due to the relative displacement between the main cable and the girder, which causes secondary stresses at the front end of hanger socket by bending because of friction between the pin and socket.

At one hanger location, two PWS ropes are arranged with a distance of 770 mm in the transverse direction and connected between the main cable and the upper chord of truss girder in each cable plane. The typical hanger consists of 85 wires of 7 mm diameter (φ7 mm × 85) and was designed with a safety factor of 2.5.

For the manufacturing error of the hangers, the requirement was defined according to the hanger length as shown in Table 1 and Fig. 1, in which the manufacturing error is divided into three representative parts. The first possible error, which occurs in "L1" in Fig. 1 is caused by the length error of the wire itself (measurement error). The second error in "L2" is caused during a pre-loading operation in which a cone inside a socket is pushed toward the rope. The third error in "L3" is a manufacturing error of the socket. The expected maximum error is 5.6 mm for hangers shorter than 50 m and 11.7 mm for the longest hanger, respectively. The length error between two hangers at one hanger location was minimized and made negligible in the design by adopting a well planned and a well-controlled manufacturing method.

Table 1
Manufacturing error of hanger in Akashi Bridge

	$L_H \leq 50$ m	$L_H > 50$ m
L1	±2.0	±L/20,000
L2	±5.0	±5.0
L3	±1.0 * 2	±1.0 * 2
Total (Max)	5.6	$\sqrt{(\Sigma\ \text{error}^2)}$

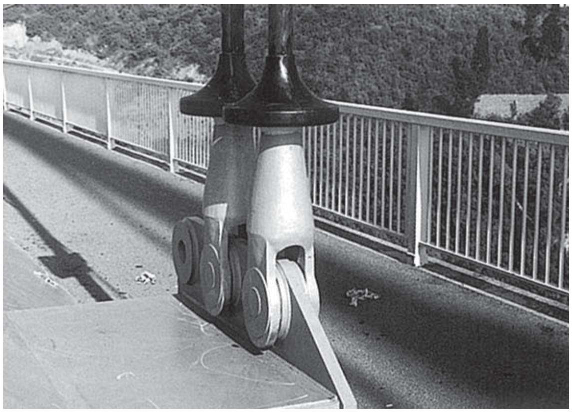

Fig. 2. Hangers at a deck anchorage (Fatih Sultan Mehmet Bridge).

2.2. *Kurushima Bridge in Japan*

Kurushima Bridge is a series of three independent suspension bridges with a main span of 600 m, 1,020 m and 1,030 m, respectively. PWS hangers with pin-ended connection are adopted to connect between the main cable and the streamlined box girder [2]. The horizontally divided clamp is adopted for the first time in Honshu-Shikoku Bridges. One hanger rope is used at one hanger location at each cable plane and the typical hanger consists of φ5 mm × 121. The requirement for maximum manufacturing errors similar to Akashi bridge was used but the constant allowable error is for hangers shorter than 60 m.

2.3. *Second Bosporus Bridge in Turkey*

Second Bosporus Bridge (Fatih Sultan Mehmet Bridge) adopts independent wire rope core (IWRC) hangers with pin-ended connection to connect between the main cable and the streamlined box girder. Two hanger ropes are used at one hanger location at each cable plane and connected to one cable clamp (Fig. 2). The hanger was manufactured within ±5 mm length error and the relative length difference of each pair of hangers less than 7 m was controlled within 5 mm. In addition, the eccentric pin at the deck anchorage is used to allow the length adjustment at site [4].

3. Difference of hanger charactreristics between two types of hanger arrangements

To examine different hanger characteristics, this numerical study employs a bridge model with a main suspension span of 3,000 m. Two types of hanger arrangements are compared numerically. One is a hanger arrangement where one hanger rope is used at a hanger location per each cable plane. The other is a hanger arrangement where two hanger ropes are used in the longitudinal direction at a hanger location per each cable plane. In the following subsections, three typical issues are numerically studied and discussed;

a) Unbalanced force among hanger ropes at one hanger location.
b) Static and Dynamic wind stability of hanger.
c) Imperfection sensitivity to a fabrication error.

3.1. *Bridge model*

The general plan view of the bridge model is shown in Fig. 3. The bridge has a main span length of 3,000 m and the sag to span ratio is 1/10. The hanger length ranges from 5 m to 306 m. Two types of hanger are modeled in this study. One is the model in which one hanger rope element is used at a hanger location per each cable plane as shown in Fig. 4 (hereinafter denoted as "1-hanger model"). This is like Kurushima Bridge shown in Section 2.2 and is a conventional modeling method even though there are two or more hanger ropes at a hanger location. The other is a model in which two hanger ropes are arranged in the longitudinal direction at a hanger location per each cable plane as shown in Fig. 5 (hereinafter denoted as "2-hangers model"), which is similar to that used at the Second Bosporus Bridge described in Section 2.3. The distance between two hangers is varied from 0.5 m to 10 m. The typical hanger spacing is 20 m and the same section area of hanger is used for the entire bridge to simplify the evaluation. The area, A = 9,275 mm^2 (φ7 mm × 241) for the 1-hanger model and A = 4,657 mm^2 (φ7 mm × 121) for 2-hangers model, respectively. The section properties of other major structural components are designed in accordance with Eurocode under some specific load

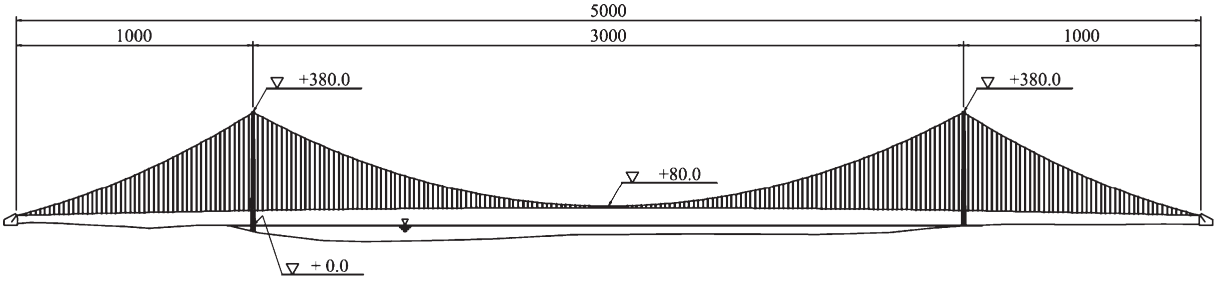

Fig. 3. Bridge model.

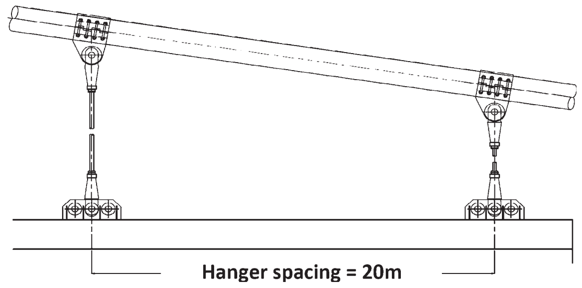

Fig. 4. 1-hanger model.

combinations and assumptions. For the deck, the same section properties and the dead weight are used along the entire bridge in this study. For all models, linearized Finite Element analysis or 2nd order analysis have been carried out by the commercial FEA-program named FANSY/BRIDGE and FANSY/LADIAN developed by CTC solutions Co., Ltd.

3.2. Unbalanced force between hangers at a hanger location

This issue is common but may fail to be noticed for the design of hangers. Under dead load condition, each hanger or hanger group supports roughly half of the dead load of deck between adjacent hanger locations and the gravity center of this half dead load, in the longitudinal direction, is almost at the relevant hanger location because the cross section and the dead load of deck are mostly the same along the bridge. This is the reason why 1-hanger model in the analysis is appropriate even if there are two or more hanger ropes at a hanger location on the real bridge. In this case, only a small negligible difference of tension due to the length difference occurs when the design hanger tension is obtained by dividing the analysis result of 1-hanger model by a number of ropes. However, the situation changes at some locations such as at the girder end and at the tower location where the dead load of deck supported by the hanger is not in the balance between the relevant hangers due to the change of cross section corresponding to the forces and the local change of hanger spacing. This is a specific issue for the bridge with multiple hanger ropes in the longitudinal direction at one hanger location per each cable plane and causes an unbalance condition between hangers. The change of unbalanced force to the hanger distance at the girder end in the 2-hangers model is shown in Fig. 6. The horizontal axis stands for the hanger distance in the longitudinal direction and the vertical one is for the increase ratio from the averaged tension in a pair of hangers based on the tension under the dead load in percentage.

The following is worth noting from the analysis of the study:

- There is a potential for a tension difference of some ±16% from the average tension in this model, under the same uniformed distributed dead load along the entire bridge. Since the unbalanced condition is emphasized in the real bridge where the dead load of the deck increases with the increase of hanger spacing at these locations, the undesirable condition in which one hanger is in compression can occur both under dead load condition and in service.
- The out of balance may require a different size of hanger at one hanger location, which is aesthetically undesirable.

To improve the undesirable condition, two practical solutions can be considered without changing the hanger spacing and arrangement.

1) To redistribute hanger tensions to be in the balance in a pair of hangers. This solution may be the simplest way at least for the hanger design, however it should be noted that this requires a pre-camber to the deck to introduce the built-in moment corresponding to the hanger tension redistribution. From a fabrication point of view, achieving a pre-camber in such a short distance at one hanger location is a big concern. Thus it is not a preferable solution.
2) The other solution is a passive one, i.e. to design hangers at one hanger location under the larger hanger tension and adopt the same dimension for the others. Of course this is limited within the certain practical range of unbalanced forces. It seems easier and more feasible since the hanger is selected among the standard lineup and likely has 10–20% margin.

3.3. Static/dynamic wind stability

One of the major issues for the design of a long span suspension bridge is to minimize the static wind load. Assuming the drag coefficients are 0.7 for the main cable and the hanger and 0.1 for the deck with the representative width of 34 m, the total drag force acting in the main span is calculated as shown in Tables 2 and 3. As is clear from these tables, to increase the number of hangers from 1 to 2 or more causes disadvantageous

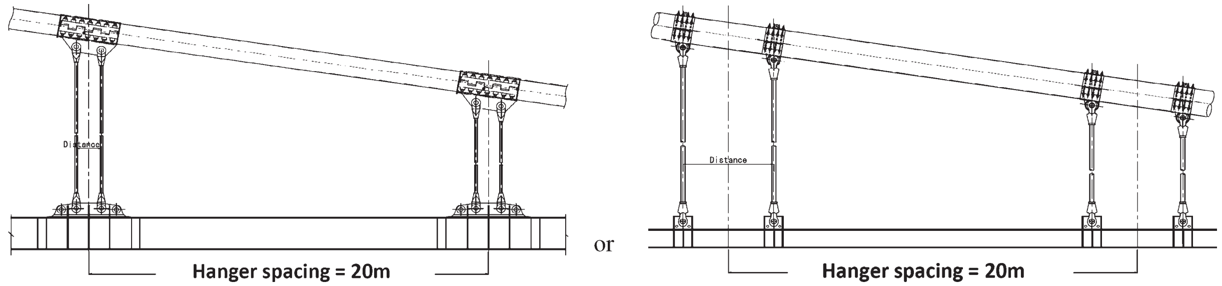

Fig. 5. 2-hangers model.

Fig. 6. Unbalanced forces in a pair of hangers.

Table 2
Drag force in the main span (1-hanger model)

	Load length (m)	Drag (N/m/bridge)
Main cable	3,080	3,343 * V^2 (29%)
Hanger	15,800	1,785 * V^2 (16%)
Deck	3,000	6,327 * V^2 (55%)
Total		11,455 * V^2 (V is the wind velocity)

Table 3
Drag force in the main span (2-hangers model)

	Load length (m)	Drag (N/m/bridge)
Main cable	3,080	3,343 * V^2 (27%)
Hanger	31,600	2,654 * V^2 (22%)
Deck	3,000	6,327 * V^2 (51%)
Total		12,324 * V^2 (V is the wind velocity)

condition with regard to drag force since the change of hanger capacity is not in proportional to the hanger diameter. In this case, the hanger diameter in the 1-hanger model is 135 mm and in the 2-hangers model is 100 mm. By adopting 2 hanger ropes at one hanger location, the drag force of the hanger increases by 49% and the total drag force acting on these components increases by 8%.

Dynamic stability presents another issue of concern. It is well known that the hanger rows or the hanger arrays have much potential oscillate due to wind. For example, “Wake galloping” for hangers arranged with a distance shorter than 6 × D (“D” is a hanger diameter) and “Wake flutter” for the hangers arranged with a distance longer than 10 × D. Though it had been said that there is low possibility for wind induced vibration for the hangers arranged between 6 × D and 10 × D, wind induced vibration with large amplitude has been observed for the leeward hanger under relatively high wind condition at the Akashi Bridge where the hanger distance is 9×D [3].

3.4. *Imperfection sensitivity*

The hanger lengths of the actual bridge are calculated using the updated cable longitudinal profile, then

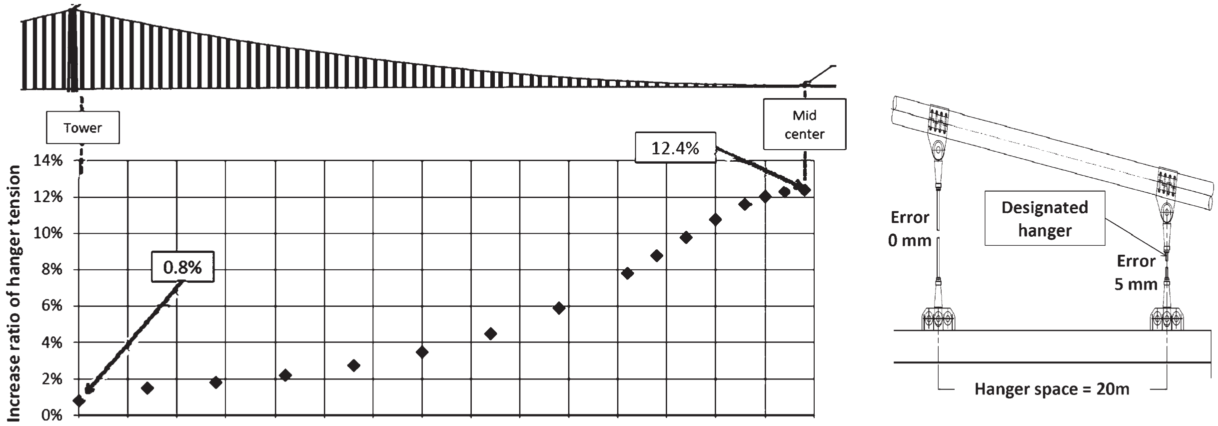

Fig. 7. Increase ratio of tension due to length error (1-hanger model).

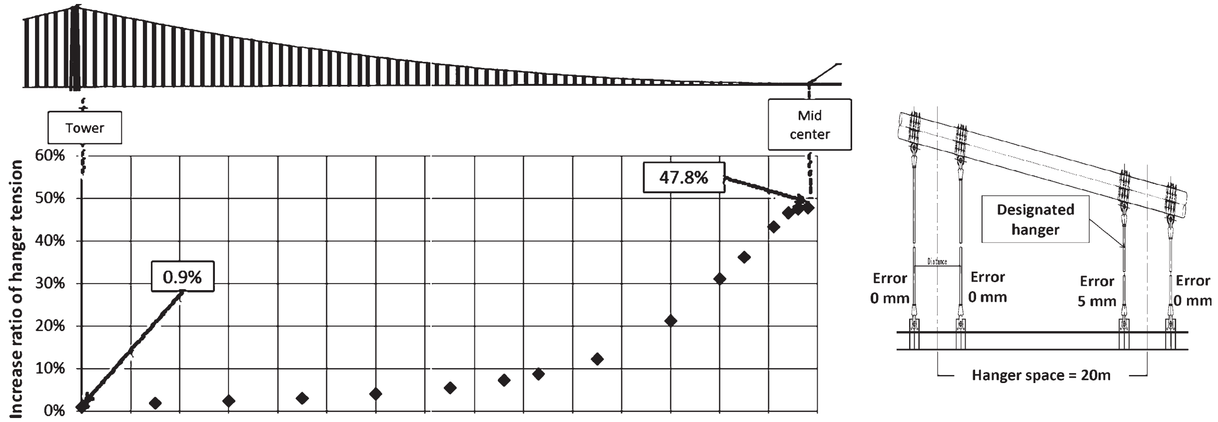

Fig. 8. Increase ratio of tension due to length error (2-hangers model, distance = 3 m).

the hangers are fabricated based on the updated information. Thus it can be said that the hanger length error is mostly caused during the fabrication. In the following subsections, an imperfection sensitivity focused on the error of unstressed hanger length is discussed. The difference between 1-hanger model and 2-hangers model is clarified through the analyses.

3.4.1. Increase ratio of tension due to length error

As a representative fabrication error of 5 mm in an unstressed hanger length, which is shorter than the design length is considered to the designated hanger in the analysis model. The other hangers have the design length; i.e. no length error. The increase of tension for the designated hanger based on the dead load condition in the main span is shown in Fig. 7 for 1-hanger model and in Fig. 8 for 2-hangers model, respectively, with a hanger distance of 3 m. The horizontal axis corresponds to the location of designated hanger to which the imperfection (length error) is added. The first on the left in the figure is the hanger closest to the tower in the main span and the right end is at the mid center. The vertical axis is the increase ratio of hanger tension from the ideal condition.

As is obvious from Figs. 7 and 8, it can be said that 1-hanger model is relatively “imperfection insensitive” and 2-hangers model is “imperfection sensitive”. The maximum increase of tension due to length error in the 1-hanger model is some 12% and this does not seem to give a critical effect on the hanger design since this value is based on the tension under dead load and the increase ratio to the design capacity is likely half or less. On the other hand, the increase of tension at the mid center in the 2-hangers model shows some 50% for

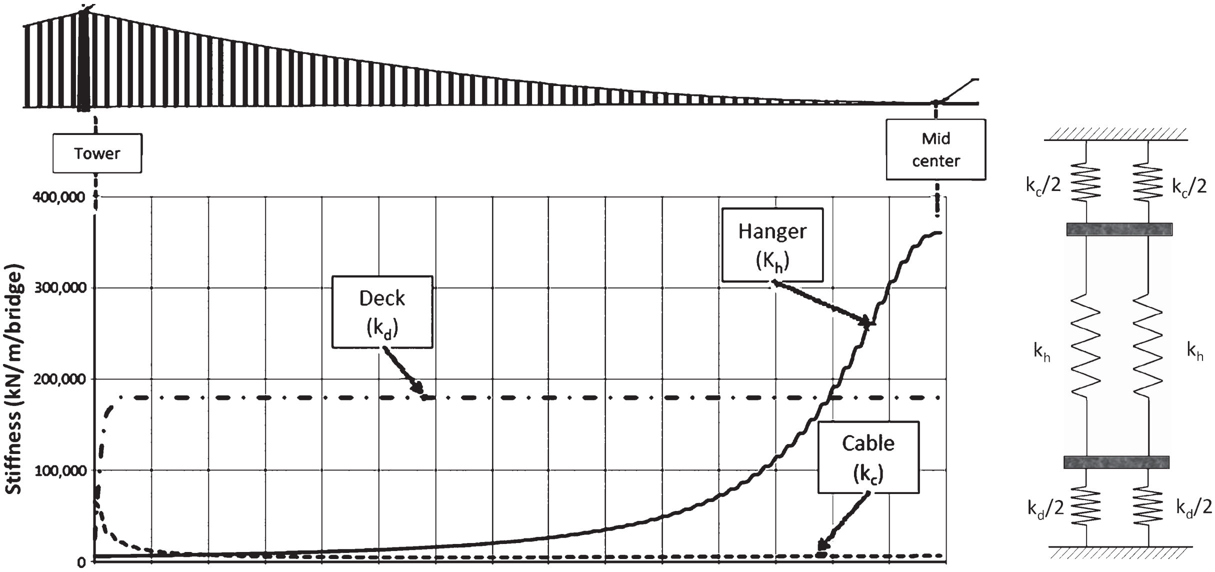

Fig. 9. Stiffness of structural components.

5 mm error of unstressed length even though this error seems to be visually negligible.

3.4.2. Relationship among structural components

Now the relationship between the hanger, main cable and the deck to the imperfection sensitivity for the hanger length error in 2-hangers model is studied in detail. In 2-hangers model, the behavior focused on one hanger location can be simplified as a spring model illustrated on the right of Fig. 9. The left of Fig. 9 shows the stiffness of each component in the main span when each hanger location is simplified as a spring model. The left end corresponds to the tower location and the right end is at the mid center. The increase ratio of hanger tension, in other words "the redistribution of unbalanced hanger load in a pair of hangers", is governed by the stiffness of the hanger and the deck since the stiffness of the main cable is negligible and contributes less to the redistribution except around the tower. It can be seen from Figs. 8 and 9 that the imperfection sensitivity suddenly becomes larger around and after the intersection point between the stiffness of the hanger and the deck. For the hangers around the mid center where the high imperfection sensitivity can be seen, the additional hanger tension due to the length error is most likely in inverse proportion to the hanger length. The relationship between the stiffness for the three elements; hanger, main cable and deck, is demonstrated in Fig. 10. It shows the difference of hanger length under dead load from the design hanger length, i.e. how the unstressed hanger length error of 5 mm in the manufacturing stage affects the tensioned hanger length under the dead load condition.

3.4.3. Effect of hanger distance

Figure 11 shows how the hanger distance in a pair of hangers affects the imperfection sensitivity of length error in 2-hangers model. The increase ratio of hanger tension due to the length error increases with shortening hanger distance. The imperfection sensitivity for the hanger at the mid center is stronger than that at the girder end because of the difference of hanger length (5 m at the mid center and 7 m at the girder end) and the stiffness of deck.

3.4.4. Case study

In the design of hanger in 2-hangers model, both effects of imperfection sensitivity for 1-hanger and 2-hangers models shall be taken into account. Thus the design condition and/or the requirement for 2-hangers model are more severe than 1-hanger model. Now an example of maximum additional hanger tension due to the length error for the hanger at the mid center in 2-hangers model with the distance of 3 m is calculated under the following conditions;

a) The unstressed length error shall be within ±5 mm.
b) The unstressed length difference in a pair of hangers shall be within 5 mm.

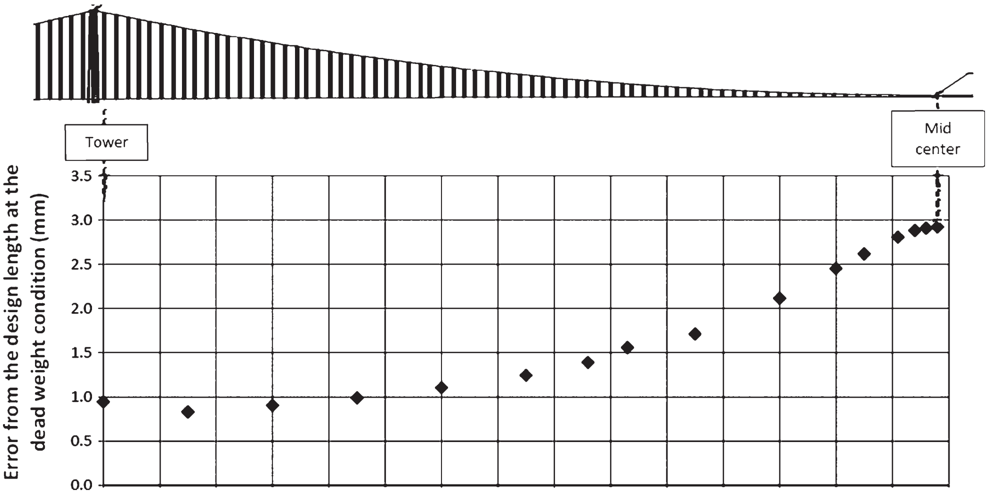

Fig. 10. Length error of hanger under the dead weight condition.

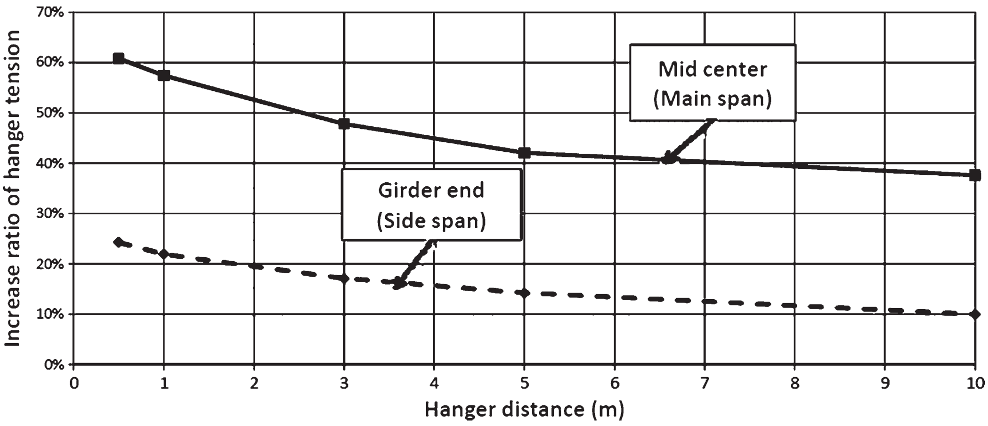

Fig. 11. Effect of hanger distance on increase ratio due to length error.

The worst condition (maximum additional tension) occurs when;

1) The designated hanger has a length error of -5 mm (shorter than the design).
2) Another hanger in a same pair is fabricated without an error.
3) Adjacent pairs of hangers are fabricated with a length error of +5 mm (longer than the design). Thus the averaged length difference between the designated pair of hanger and the adjacent one is 7.5 mm.

In this case, the maximum additional tension can be expected for the hanger at the mid center as 48% + 2 * (7.5/5) * 12 = 84% by using the analysis results shown in Figs. 8 and 9. Thus the hanger tension under the dead load increased by 84%, based on the ideal condition, should be used as a design value. In reality, it can be said that the conditions defined in this case study are not practical from the design point of view and more severe requirement needs to be considered for short hangers. For example, by changing the above conditions a) and b) to

a’ The unstressed length error shall be within ±3 mm and
b’ The unstressed length difference in a pair of hangers shall be within 1.5 mm.

In such case, the maximum additional tension would be 48% * (1.5/5) + 2 * (7.5/5) * 12% * (3.75/7.5) = 32%

and it seems to be acceptable in the design. These severe requirements shall be limited to a small number of hangers located near the mid center.

3.4.5. Possible solutions

Some kind of change or careful attention from the conventional method is required in the design, fabrication and construction for 2-hangers model since the requirements a') and b') in the case study seem to be difficult to achieve if the conventional method is used. Two possible solutions for how to achieve such severe requirements in reality are described below.

To adopt the eccentric pin to allow the adjustment at site by turning the pin connected between the hanger socket and the deck anchorage/the clamp is one solution. The pin with 3 mm difference of rotation center between two axes crossing right angles can achieve the requirements a') and b'). There are a few experiences of eccentric pin.

Another solution is to change the fabrication process. Thus finishing pin hole at a socket is carried out after a pre-loading operation since a major possible error occurs during the pre-loading operation. The pin hole at a socket smaller than the design value is made prior to a pre-loading, then finishing the pin hole to the design diameter is carried out with a consideration for the measured result of hanger length after the pre-load operation.

Since these two solutions produce somewhat disadvantageous results related to cost and workability, the suitable balance among design, cost and workability should be studied in detail for design of long suspension bridge with this type of hanger arrangement.

4. Conclusions

The characteristics of hangers for a suspension bridge have been studied in this paper. The difference between 1-hanger model and 2-hangers model was especially discussed in detail through the analysis results by using a bridge model with a main span of 3,000 m. the following conclusions are noted:

1. Hanger arrangement type: The 2-hangers model, where a bridge has two or more hanger ropes in the longitudinal direction at each hanger location per each cable plane, shows more complex and sensitive characteristics than 1-hanger model, e.g., the unbalanced forces and the imperfection sensitivity to unstressed length error. Except for the situation that 1-hanger model is not feasible for example because of too large diameter of hanger, it seems better not to adopt 2-hangers model as a hanger arrangement type.
2. Requirements for fabrication: The allowable fabrication error for unstressed hanger length shall be distinguished between the hanger arrangement types. For 1-hanger model, a similar concept to past experiences can be suitable but the upper limit for long hanger rope needs to be defined for a suspension bridge with a main span longer than 2,000 m. The upper limit of error of 15 mm seems to be practical since the error of long hangers located near tower does not much affect on the additional hanger tension and the deformation (imperfection to a bridge geometry). For 2-hangers model, more severe requirement and/or concept than past experiences, which were likely based on 1-hanger model need to be defined.
3. Size effect: Through this study, the so-called major "Size-effect" for a longer span suspension bridge is not seen compared with the past experiences. Although some issues such as the rotational deformation which likely becomes larger with an increase of main span length and may causes a critical secondary stress due to the bending are not covered here, it can be said that the conventional method is applicable and extended for the hanger of a longer span suspension bridge in the future by taking findings in this study into consideration.

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