【論文】

Proposal for Hybrid Stress-Ribbon Vehicle Bridges
Part 2. Preliminary design of cables

Takehiko Harada[†], Takeshi Yoshimura[†], Yoji Mizuta[†], Takahisa Tanaka[†], Takuma Beppu[‡], Hideo Jo[‡†], Niels J. Gimsing[‡‡] and Won-Ho Kang[‡‡†]

ハイブリッド吊床版道路橋の提案
（その２）ケーブルの試設計

原田 健彦[†]，吉村 健[†]，水田 洋司[†]，田中 孝久[†]，別府 琢磨[‡]，
城 秀夫[‡†]，N. J. ギムスィング[‡‡]，姜 圓鎬[‡‡†]

Abstract: In 'Part 1' of this study, hybrid stress-ribbon vehicle bridges with a span length of L = 200, 400 or 600 m are proposed, and the preliminary design of superstructure and the examination of their static characteristics are made. The details of the preliminary design of upper and lower cables of the bridges are reported here as 'Part 2' of this study. Also the static characteristics of cables were examined. The findings revealed that the total number of the upper and lower cable strand was respectively found to be 16, 40 and 60. The diameters of the 16-, 40- and 60-strand single cable were estimated to be 26, 40 and 50 cm and are not too large. Also it was found that the deflection and deformation of girder was well controlled by the upper cable and that the maximum normal force in the lower cable was 90% of the resisting force.
Keywords: hybrid stress-ribbon vehicle bridge; suspension bridge; preliminary design; static characteristics.

1. Introduction

In 'Part 1' of this study[1)], hybrid stress-ribbon vehicle bridges with a span length of L = 200, 400 or 600 m are proposed, and the preliminary design of superstructure and the examination of their static characteristics are made. The findings revealed that the weight of the stiffening truss girder per unit area was about half of a streamlined steel box girder for a conventional suspension bridge. Regarding the static characteristics, the deformation and deflection of girder were well controlled by the upper cable, and the maximum normal force in the lower cable was 90% of the resisting force. Therefore, the above results suggest that the design concept for the proposed hybrid stress-ribbon structure could be applied to vehicle bridges with a single span of 200-600 m.

The discussion in part 1 of this study was partially based on the results obtained in the preliminary design of the upper and lower cables. The details in the preliminary design of the cables are partly reported in Ref. 2 and wholly described below as 'Part 2' of this study. A 2D numerical analysis was made to estimate the optimum cross-sectional area of each cable, and static characteristics of the bridges are examined.

2. Outline of proposed structures

Fig. 1(a) presents our proposal for a hybrid stress-ribbon bridge. The bridge has a single span of L = 400 m. The effective width of the girder is 10.5 m with two traffic lanes and one sidewalk (Fig. 1(b)). As shown in Figs. 1(a) and (c), the superstructure of this proposed bridge consists of the reinforced concrete towers, the upper and backstay cables supported by the towers, the lower cables stayed by the ground-anchored abutments and the girder. The 13 m wide steel girder is composed of a pair of edge beams of circular pipe with a diameter of 70 cm, the open-grating deck plate, the I-shaped floor beams with varying depth of 0.7-2 m., the upper lateral bracings and the lower inclined bracings. The sag ratios (f/L) of the upper cable and lower cable are 0.1 and 0.02, respectively.

In 'Part 2' of this study, a preliminary design was made not only for the proposal of the bridge with L = 400 m but also for the other proposal of two bridges with L = 200 and 600 m. In these bridges, it is assumed that the dimensions of the girder, the sag ratios of the cables

[†] Dept. of Civil & Urban Design Eng., Kyushu Sangyo Univ.
[‡] Yokogawa Construction Co., Ltd.
[‡†] Fukuoka Branch, Structural Engineering Center Co., Ltd.
[‡‡] Dept. of Civil Eng., Technical Univ. of Denmark
[‡‡†] Division of Construction, Collage of Eng., Dong-A Univ.

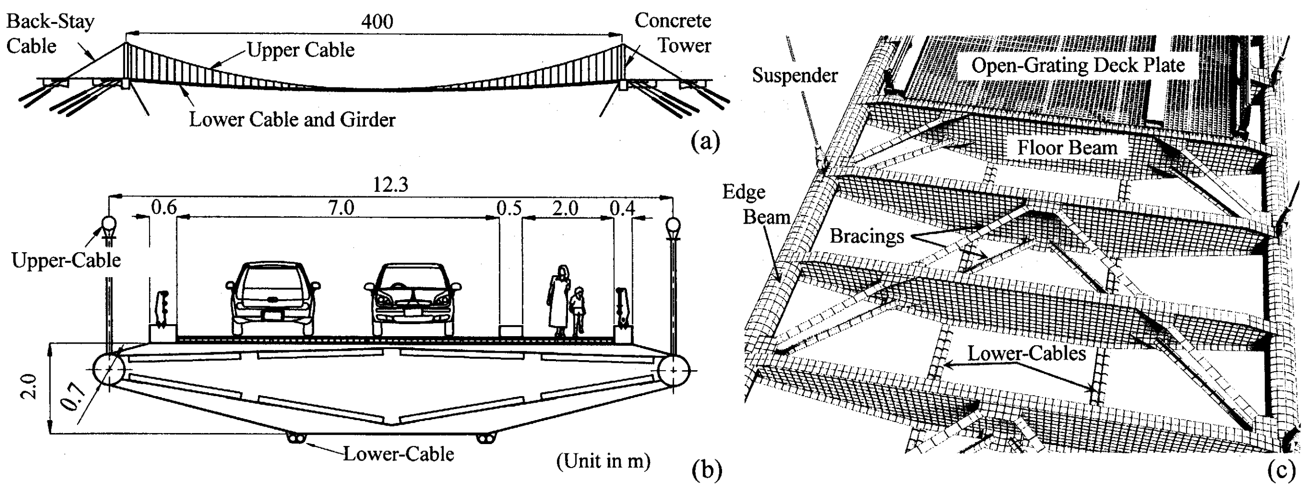


Fig. 1 The side view, (a), and the cross-section and CG of the girder, (b) and (c), for the hybrid stress-ribbon vehicle bridge.

and the material of the superstructure are the same.

3. Outline of preliminary design of upper and lower cables

The dead load and live load used in the cable design are listed in Table 1. The live load in the table was estimated based on A-live traffic load and footway track load specified in the specification of Japan highway bridges. In the table, only the dead load of girder, w_G, is listed and that of cables is not included.

The parallel-wire strands, PWS-127, were used for the upper and lower cables. The dimension of the strand is listed in Table 2. The optimum required number of the upper and lower cable strands was determined in the preliminary design by a 2D numerical analysis. In the analysis, the optimum number of cable strands was determined in the following manners: the maximum deflection of the girder was below the allowable value of $L/350$, and the maximum normal stress in the upper and lower cables was below the allowable value of 590 MPa. Note that both the upper and lower cables were subjected to uniform dead load of girder, w_{GU} and w_{GL} ($w_G = w_{GU} + w_{GL}$), and that the initial tensile force in the upper and lower cables was respectively induced by w_{GU} and w_{GL} together with the dead load of each cable itself.

The deflection of the girder and the normal force in the upper and lower cables can be controlled by the following three parameters: (1) the number of upper cable strand per one cable, N_U (equivalent to the cross-sectional area of upper cable); (2) the number of lower cable strand per cable, N_L (equivalent to that of lower cable); (3) the ratio of uniform dead load subjected to the lower (upper) cable in the entire span to dead load of girder, w_{GL}/w_G (w_{GU}/w_G).

In the following sections, the preliminary design of cables for the structure with L = 400 m is introduced first, and then that for the structures with L = 200 and 600 m is described.

Table 1 The dead load and live load used in the cable design.

Dead load		
Girder, w_G	3.5	[kN/m^2]
Live load		
p_1	10	[kN/m^2]
p_2	3.0	
footway track	3.0	

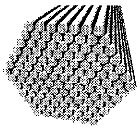
4. Bridge with L = 400 m

4.1. Influence lines

The absolute maximum values of both girder deflection and cable tensile force were obtained by the influence line analysis. Figs. 2(a)-(c) show the typical examples of three kinds of influence line of girder deflection and the normal force in the upper and lower cables at 0, $L/8$, $L/4$, $3L/8$ and $L/2$. These figures are the results for N_U = 20 and N_L = 20. It should be noted that different characteristics can be observed in the influence lines between normal force in the upper cable (a) and the lower cable (b). This phenomenon suggests that the lower cable functions rather as the cable itself than as the lower chord of the stiffening truss (see section 4.2 in part 1 of this study[1)]).

The influence line is the function of three parameters, N_U, N_L and w_{GL}/w_G. Therefore, in the analysis for obtaining the optimum required numbers of the upper and lower cable strands, which is hereafter referred to as the 'strand analysis', the same large number of influence lines as the number of combination of these three parameters were necessary.

Table 2 The dimension of parallel-wire strand, PWS-127.

Number of wire	Shape and size [mm]	Cross-sectional area [mm²]	Guaranteed minimum tensile strength [kN]	Weight [N/m]
127-ϕ5mm	 57x65	2490	4400	192

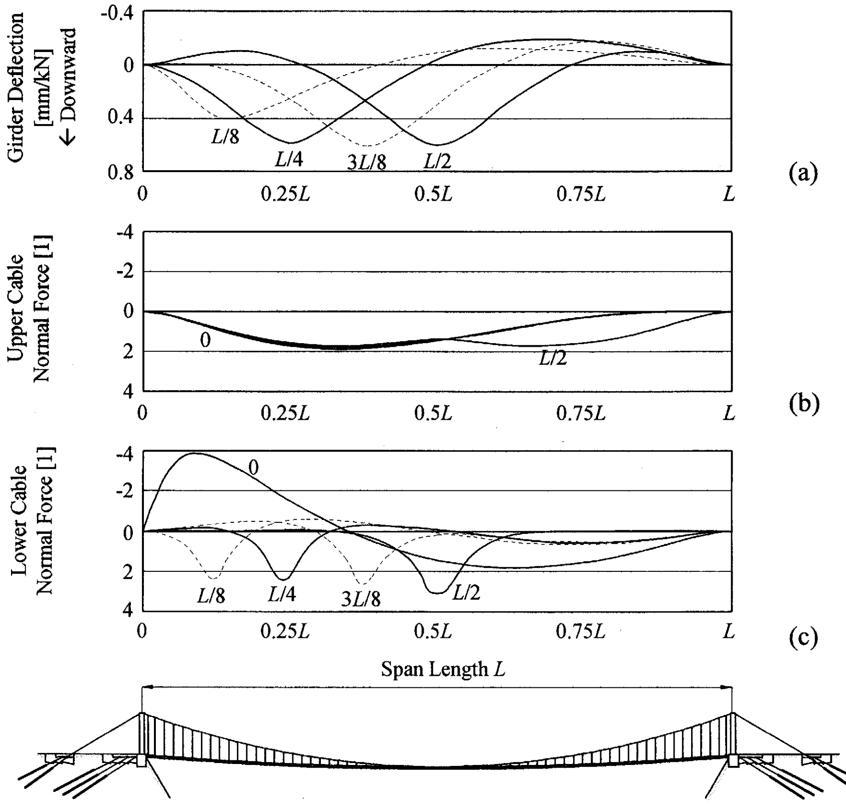


Fig. 2 The typical examples of influence lines of girder deflection and the normal force in the upper and lower cables at 0, $L/8$, $L/4$, $3L/8$ and $L/2$.

4.2. Three parameters

Before the strand analysis, the effects of three parameters on the response of the bridge, i.e., on the maximum girder deflection, δ_y, the maximum normal stress in the upper cable, σ_U, and the maximum normal stress in the lower cable, σ_L, were examined. During the examination, the numerical values of two of three parameters were fixed and that of one parameter was varied. The fixed numerical values of the parameter were $N_U = 20$, $N_L = 20$ and $w_{GL}/w_G = 0.25$.

Figs. 3-5 show the results for the cases when N_U, N_L and w_{GL}/w_G were respectively variables (the ordinates represent these variables in the figures). In these three figures, Figs. (a)-(c) respectively show δ_y, σ_U and σ_L. It can be observed in Fig. 3 that σ_L hardly depended on N_U, and both δ_y and σ_U strongly depended on N_U. While σ_L strongly depended on N_L as can be seen in Fig. 4. Fig. 5 shows that σ_L also strongly depended on w_{GL}/w_G.

4.3. Procedure of strand analysis

As was shown in Fig. 3(c), σ_L hardly depended on N_U. Based on this fact, N_L was fixed to some value, first, and w_{GL}/w_G was decided in such a way that σ_L was close to the allowable value. As was shown in Figs. 3(a) and (b), δ_y and σ_U strongly depend on N_U. Therefore, δ_y and σ_U were calculated by varying N_U, next. And then the optimum value of N_U for the fixed N_L was calculated in such a way that δ_y and σ_U were close to the allowable values.

Further analyses were repeated for different N_L and the smallest combination of $N_U + N_L$, that is, the optimum total number of strands was found.

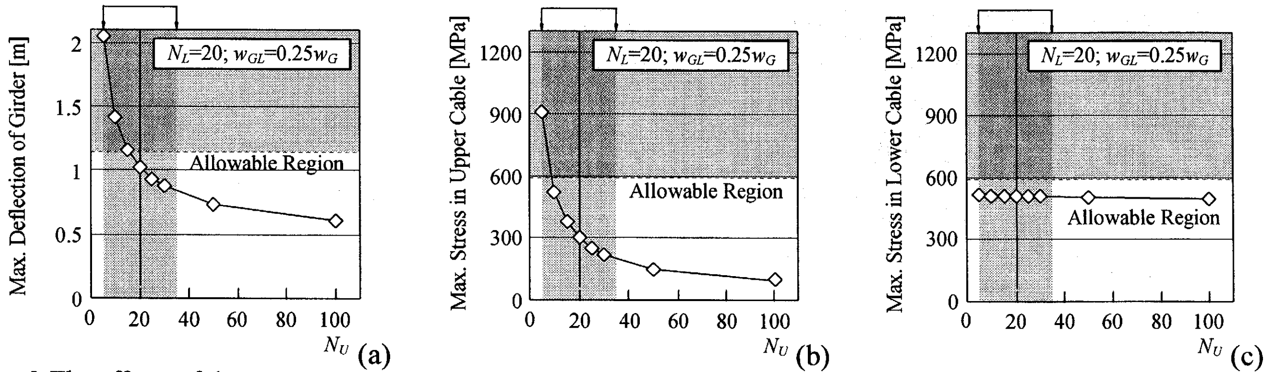


Fig. 3 The effects of three parameters on the response. The variations of the maximum deflection of girder δ_y, (a), and the maximum normal stress in the upper and lower cables σ_U and σ_L, (b) and (c). 'The number of the upper cable strand, N_U': a variable; the other two parameters: fixed.

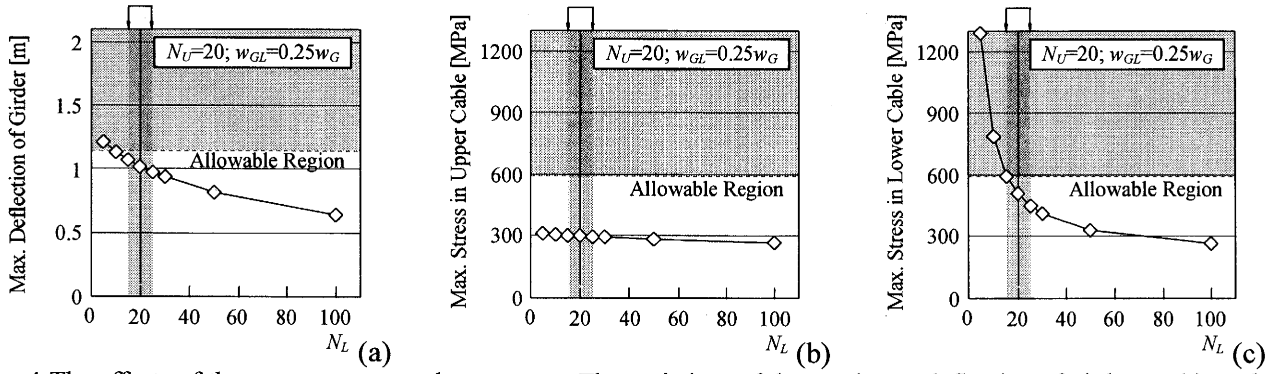


Fig. 4 The effects of three parameters on the response. The variations of the maximum deflection of girder δ_y, (a), and the maximum normal stress in the upper and lower cables σ_U and σ_L, (b) and (c). 'The number of the lower cable strand, N_L': a variable; the other two parameters: fixed.

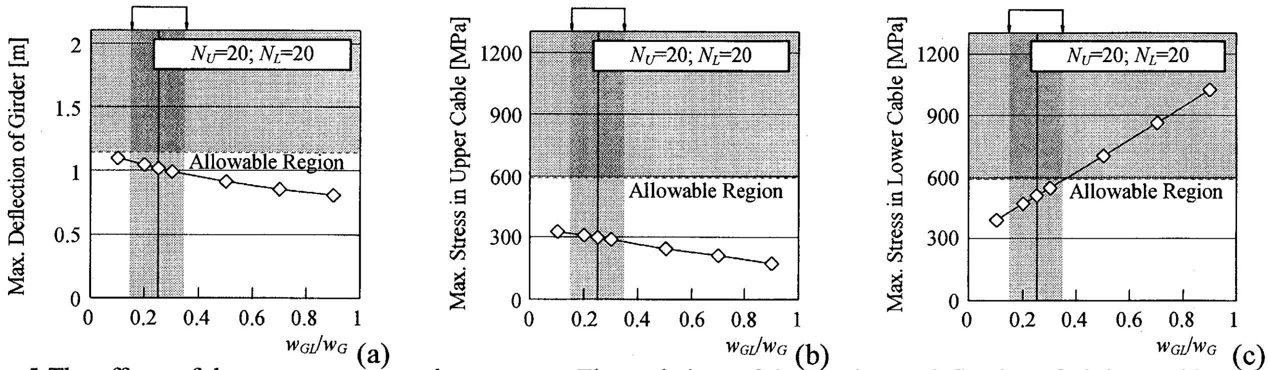


Fig. 5 The effects of three parameters on the response. The variations of the maximum deflection of girder δ_y, (a), and the maximum normal stress in the upper and lower cables σ_U and σ_L, (b) and (c). 'The ratio of dead load subjected to lower cable to dead load of girder, w_{GL} / w_G': a variable; the other two parameters: fixed.

4.4. Preliminary strand analysis

Before performing the detailed strand analysis, a preliminary analysis was made by using more than one hundred of combinations of three parameters, N_U, N_L and w_{GL}/w_G, and the examination was made by trial and error. Findings revealed that the value of these three parameters which was necessary to be varied was in only the narrow ranges centered on N_U = 20, N_L = 20 and w_{GL}/w_G = 0.25 as shown in Figs. 3-5by the arrows.

According to the procedure of strand analysis discussed in section 4.3, the number of N_L was fixed at 15, 20 or 25 and that of N_U was varied from 5 to 35. The examination by trial and error showed that the optimum value of w_{GL}/w_G was found to be 0.15, 0.25 or 0.35. In other words, the prestress introduced to the lower cable is due to the uniform dead load of 0.15w_G, 0.25w_G or 0.35w_G together with the cable weight.

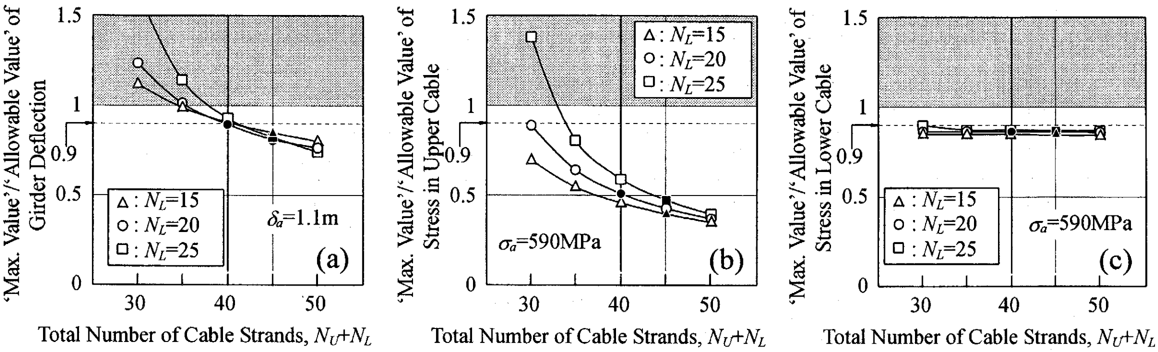


Fig. 6 The results of cable strand analysis for the bridge with L = '400 m'. The maximum girder deflection, (a), and the maximum normal stress in the upper and the lower cables, (b) and (c) vs. the total strand number, $N_U + N_L$.

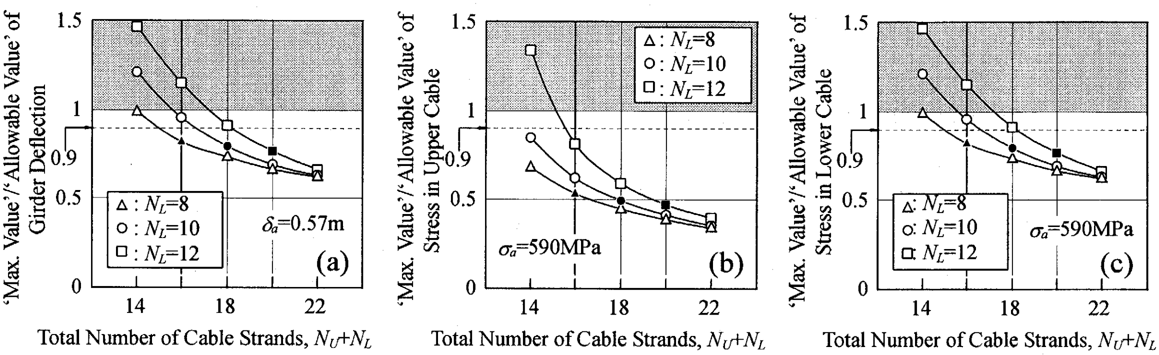


Fig. 7 The results of cable strand analysis for the bridge with L = '200 m'. The maximum girder deflection, (a), and the maximum normal stress in the upper and the lower cables, (b) and (c) vs. the total strand number, $N_U + N_L$.

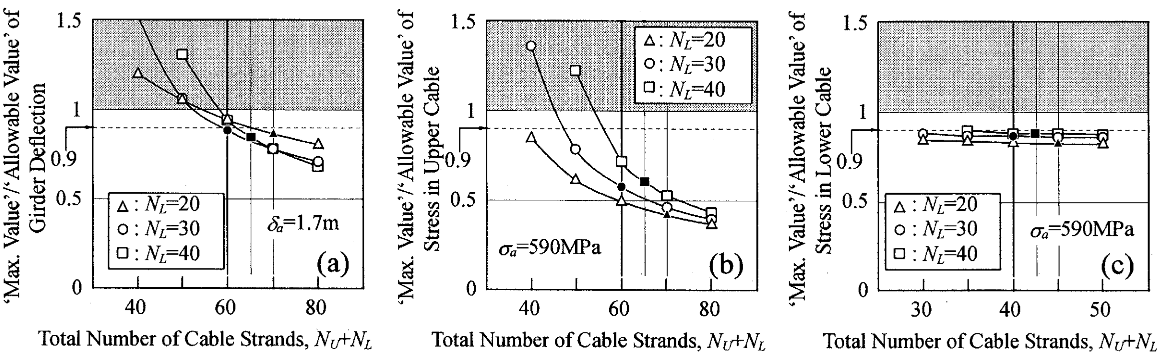


Fig. 8 The results of cable strand analysis for the bridge with L = '600 m'. The maximum girder deflection, (a), and the maximum normal stress in the upper and the lower cables, (b) and (c) vs. the total strand number, $N_U + N_L$.

6.2.5. Results of strand analysis

Figs. 6(a)-(c) respectively illustrate the variation of the maximum values of girder deflection, δ_y, that of stress in the upper cable, σ_U, and that of stress in the lower cable, σ_L. Note that the abscissa represents the total number of strand, $N_U + N_L$. In the figure, the lower boundary of the shadowed area denotes the standardized allowable value of 1 and the broken line denotes 90% of the allowable value that was considered to be the 'criterion' in the strand analysis. As can be seen in Fig. 6(c), σ_L hardly depends on N_U and almost clear the 'criterion'. As regards σ_U, every case examined was below the 'criterion' except for the case of $N_L = 25$ & $N_U = 5$ as shown in Fig. 6(b). Therefore, the optimum value of N_U can be determined by the allowable value of the girder deflection, δ_y presented in Fig. 6(a).

From Fig. 6(a), the minimum total required number of cable strands in these three cases can be estimated to be 45 in the 15-strand lower cable & 30-strand upper cable system denoted by ▲ in the figure; 45 in the 25-strand lower cable & 20-strand upper cable system (mark ■); and 40 in the 20-strand lower cable & 20-strand upper cable system (mark ●). Therefore, it can be concluded that the optimum total required number of cable strands were 40. The diameter of 40-strand single cable is estimated to be about 40 cm.

Table 3 The results of strand analysis for three bridges.

L [m]	N_U+N_L	N_U	N_L	w_{GU}/w_G	w_{GL}/w_G	w_C [kN/m/Br]
200	16	8	8	0.7	0.3	6.14
400	40	20	20	0.75	0.25	15.4
600	60	30	30	0.85	0.15	23.0

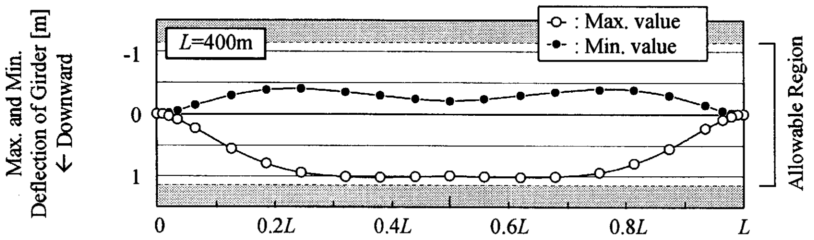


Fig. 9 The maximum and minimum deflection of girder for the bridge with L='400 m'.

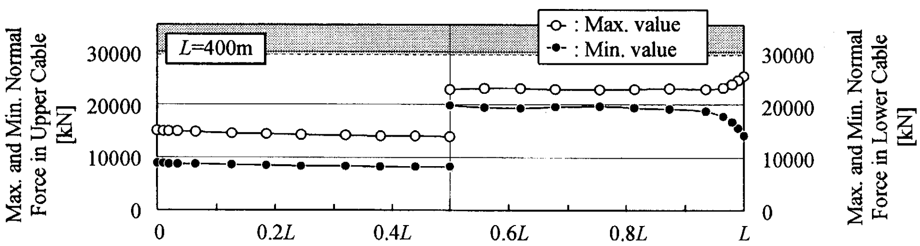


Fig. 10 The maximum and minimum normal force in the upper and lower cables for the bridge with L='400 m'.

5. Bridges with L = 200 and 600 m

The strand analyses were made for the other two bridges with L = 200 and 600 m. Figs. 7 and 8 respectively show the variation of the maximum values of girder deflection, δ_y, that of stress in the upper cable, σ_U, and that of stress in the lower cable, σ_L (cf. Fig. 6). The results from Figs. 6-8 for three bridges are summarized in Table 3. The findings revealed that for the bridges with the span length of 200, 400 and 600 m, the optimum total number of strands was respectively found to be 16, 40 and 60. The diameters of 16-, 40- and 60-strand single cable were estimated to be 26, 40 and 50 cm and were not too large.

6. Static characteristics

6.1. Bridge with L = 400 m

6.1.1. Deflection of girder

Fig. 9 presents the maximum (downward) and minimum (upward) deflection diagram of girder. The maximum deflection of about 90% of the allowable value, which was the 'criterion' in the analysis, was observed in a relatively wide range of L/4 - 3L/4, while the minimum deflection was far below the allowable value in the entire span.

6.1.2. Normal force in upper and lower cables

Fig. 10 illustrates the maximum and minimum normal force diagram in both the upper and the lower cables. The maximum normal force in the lower cable of about 90% of the resisting force, which was the 'criterion' in the analysis, was observed not in a wide range of the span but only at the abutment. While, the maximum normal force in the upper cable was far below the resisting force as the upper cable mainly functions as the structural member to control the deformation and deflection of the girder. It should be noted that the minimum normal force in the lower cable was verified not to be negative but to be positive; i.e., that the compressive axial force was not induced in the lower cable. Although the compressive axial force can be induced in the lower cable under live load (see negative area in Fig. 2(c)), the compressive force was cancelled by the initial tensile force due to w_{GL} and the cable weight.

6.2. Bridge with L = 200 or 600 m

Figs.11 (a) and (b) show the maximum (downward) and minimum (upward) deflection diagram of girder for the other two bridges with L = 200 and 600 m, respectively. Qualitatively, a nominal difference can be

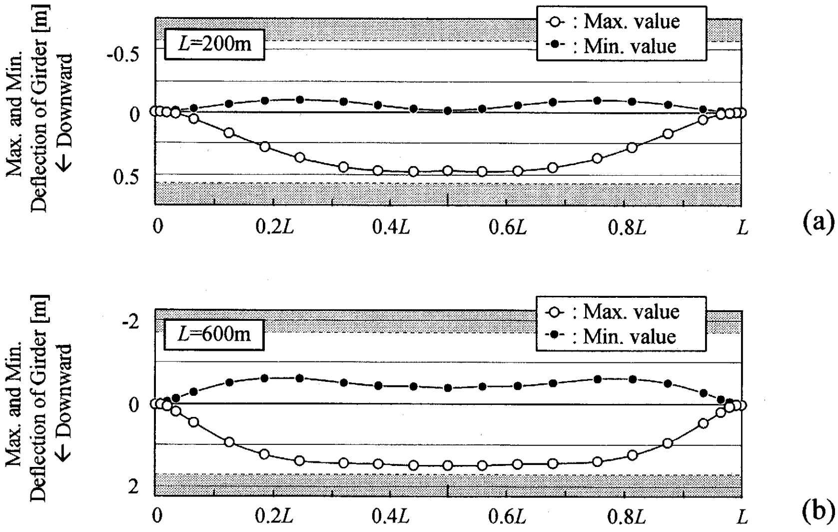


Fig. 11 The maximum and minimum deflection of girder for the bridges with L='200 m' and '600 m', (a) and (b).

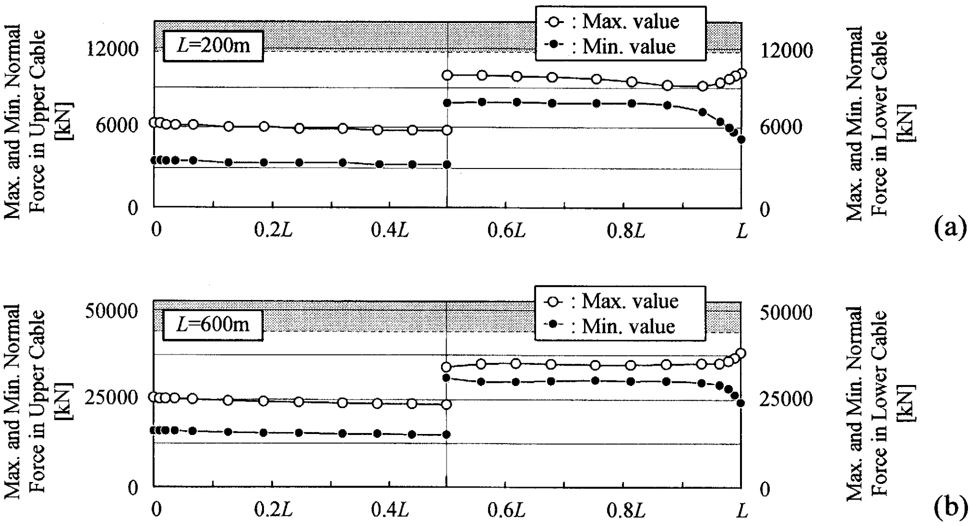


Fig. 12 The maximum and minimum normal force in the upper and lower cables for the bridges with L='200 m' and '600 m', (a) and (b).

seen between these figures and Fig. 9 for the bridge with $L = 400$ m.

Figs. 12(a) and (b) illustrates the maximum and minimum normal force diagram in both the upper and the lower cables for the other two bridges with $L = 200$ and 600 m, respectively. Qualitatively, a nominal difference also can be seen between these figures and Fig. 10 for the bridge with $L = 400$ m.

8. Conclusions

The main results obtained in this study are summarized as follows:

1. For the bridges with the span length of 200, 400 and 600 m, the total number of the upper and lower cable strand was respectively found to be 16, 40 and 60. The diameters of the 16-, 40- and 60-strand single cable were estimated to be 26, 40 and 50 cm and are not too large.
2. The deflection and deformation of girder was well controlled by the upper cable. The maximum deflection was 90% of the allowable value.
3. The maximum normal force in the lower cable was 90% of the resisting force. Also, the minimum normal force in the cables was positive, i.e., compressive axial force was not induced in the cables.

Further studies that should be made in order to realize the construction of the proposed hybrid bridges, which is the final objective of this study. The studies include the following subjects:

- Wind tunnel model study to examine the aerodynamic stability of the structures both during the erection of girder and after completion.
- The seismic design of the structures.
- Economical evaluations.
- Temperature stress and fatigue.

The static characteristics of structures during the erection of girder has already been made and is reported in Ref. 3.

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