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Development of a Program for Analyzing Visco-Elastic Behavior of Cable Supported Steel Bridges

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Synopsis

Developed in the present study is an analytical program for cable supported steel bridges, in which the viso-elastic behavior of bridges can be considered. The analytical program consists of two parts, one is for the analysis of the visco-elastic behavior, and another part is for the FEM analysis of the overall structures. The visco-elastic behavior is evaluated by using a three-element model. Then the applicability of the program is discussed using simplified models. Finally, the long-term behavior of cable-stayed bridges with steel cables or carbon fiber reinforced plastics (CFRP) cables are investigated by using this program.

KEYWORDS: visco-elasticity, cable-stayed bridges, long-term behavior, steel cable, CFRP cable

1. Introduction

In Japan, bridges with cables such as cable-stayed bridges have and Nielsen bridges been frequently constructed recently due to their rational mechanical properties. However, since the cables, which are very important structural elements, show visco-elastic behavior, their stress and strain vary with time. As a result, due to such a visco-elastic behavior significantly large stress or large displacement may occur during the bridge service period. Therefore, in order to maintain the performance of such bridges, long-term behavior should be precisely predicted in advance.

In the present study, the analytical program for two dimensional framed models considering the visco-elastic behavior of cables was developed at first. In this program, finite deference method is used for the analysis on the visco-elastic behavior of cables, and FEM is utilized for the structural analysis at each time step. Secondly, in order to investigate long-term behavior of cable-stayed bridges, the program was applied to two cable-stayed bridge models, one with steel cables, another with carbon fiber reinforced plastics cables (CFRP).

2. Development of Analytical Program

2.1 Outline of the developed analytical program

A flow-chart of the program is shown in Fig. 1. First, the FEM analysis[1)] is carried out at time t_0. Then, in order to obtain the increment of tensile force in each cable, Δf_{ic}, the time dependent behavior analysis of cables is carried out by using the finite deference method at $t = t_0 + \Delta t$. Using the obtained incremental forces in each cable, Δf_{ic}, the FEM analysis the at time $t_0 + \Delta t$ is carried out. As a result, the bridge behavior can be obtained at $t = t_0 + \Delta t$. This process shall be repeated until the target time.

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2.2 Modeling of Visco-Elastic Behavior on Steel Cables

The three-element model as shown in Fig. 2 is applied for modeling the visco-elastic behavior of steel cables. This model is well known as one of the simplest models for representing such a behavior. It consists of both a spring element and the Voigt (Kelvin) element. In this figure, E_1 and E_2 denotes Young's modulus and η, the coefficient of viscosity. Constitutive equation of this model is as follows:

$$\frac{d\varepsilon_c}{dt} = -\frac{E_2}{\eta}\varepsilon_c + \frac{\sigma}{\eta} \qquad (1)$$

where

ε_c : creep strain
σ : stress
η : coefficient of viscosity
ε_e : elastic strain

$$\left(\varepsilon_e = \frac{\sigma}{E_1}\right) \qquad (2)$$

Constants, such as E_1, E_2 and η are determined based on the experimental measurements.

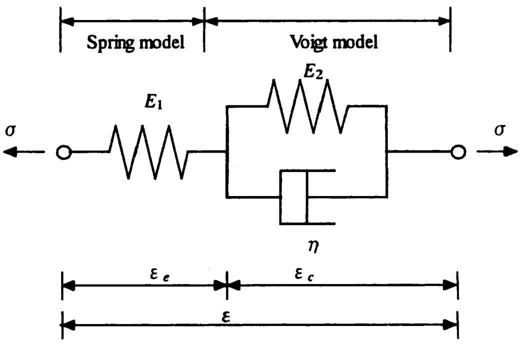


Fig. 2 Three-element model

2.3 Modeling of behavior on Carbon Fiber Reinforced Plastics Cables (CFRP)

CFRP cables have better characteristics, such as higher strength, resistance to erosion, and lighter weight, compared with steel cables. Therefore, significant decrease in dead load can be expected by using these cables.

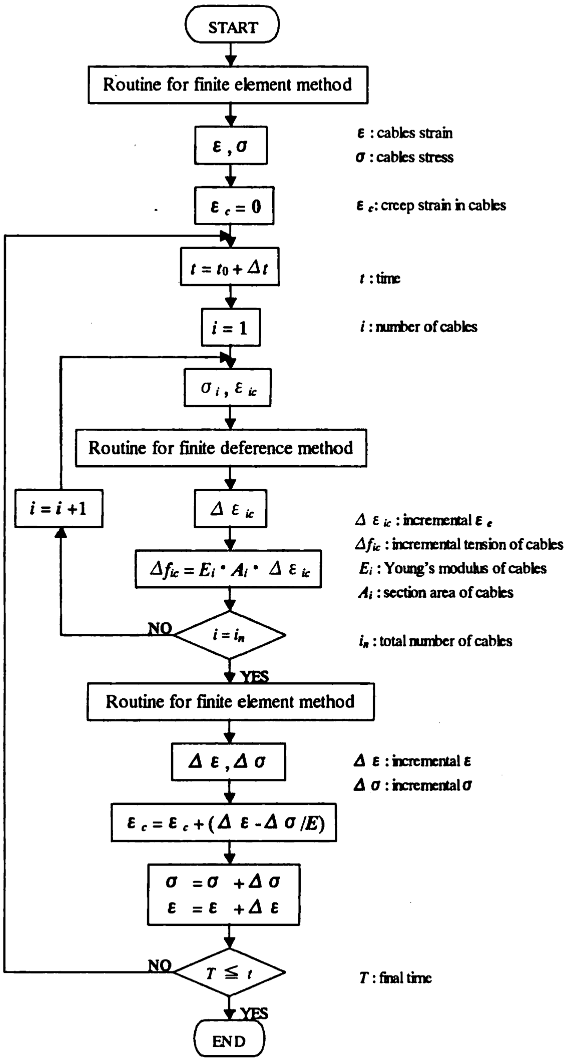


Fig. 1 Flow-chart of the developed program

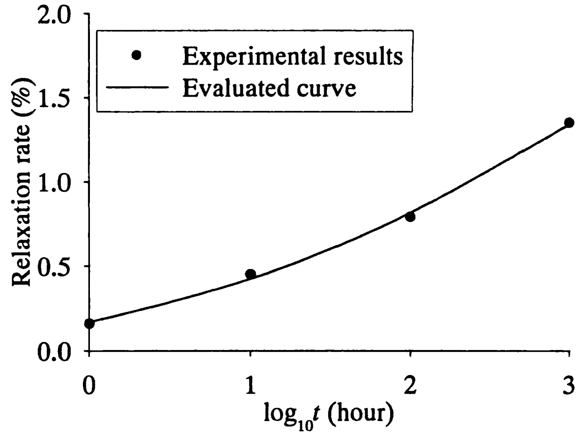


Fig. 3 Relaxation rate vs. time

The relaxation curve of a CFRP cable obtained from experiments is shown in Fig. 3, and the material properties, in Table 1[2]). Based on these experimental results, the relationship between relaxation rate vs. time is evaluated by non-linear regression analysis as follows:

Table 1 Material properties of CFRP cable

	nominal diameter	norminal cross sectional area	characteristic strength	elastic modulus	unit weight
unit	mm	mm^2	kN	N/mm^2	N/mm
CFRP Cable	35	698.8	980	1.18×10^5	1.10×10^{-2}

$$\frac{\Delta\sigma}{\sigma_0} = 0.0675(\log_{10}t)^2 + 0.1885\log_{10}t + 0.1685 \qquad (3)$$

where

t : time (hour)

σ_0 : initial stress

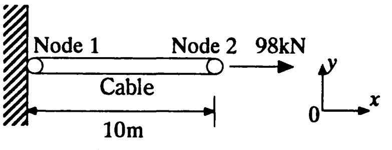
$\Delta\sigma$: increment stress

From this figure, it is found that the regression results agree well with the experimental ones.

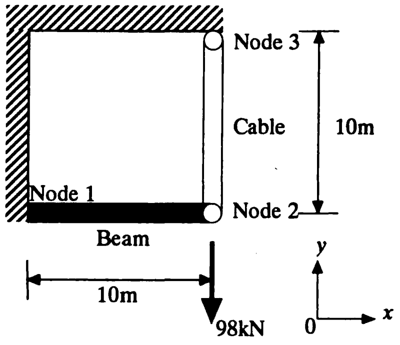
2.4 Verification of the Developed Analytical Program

In order to check the applicability of the developed program, the visco-elastic behavior of simplified models, as shown in Fig. 4, have been investigated using this program. In case of the model A, the stress is kept constant, and on the other hand, the stress is variable in case of the model B. In this analysis, the time step of 0.1 year is adopted. Material properties applied in the analysis are summarized in Table 2.

The analytical results are shown in Figs. 5 and 6. At the same time, theoretical solutions are also shown in these figures. From these figures, it is observed that the analytical results of these two cases are almost identical to the theoretical results. Accordingly, the developed program can be applied to the analysis of the visco-elastic behavior of cable bridges.



(a) model A



(b) model B

Fig. 4 Outline of the simplified models

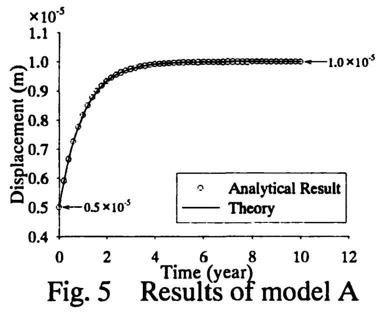


Fig. 5 Results of model A

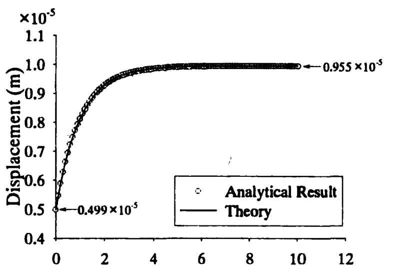


Fig. 6 Results of model B

Table 2 Material properties

Member	E_1 (N/mm²)	E_2 (N/mm²)	η (year・N/mm²)
Cable	1.96×10^5	1.96×10^5	1.96×10^5
Beam	2.06×10^5	-	-

3. Application to long-term behavior analysis of cable-stayed bridges

3.1 Analytical model

The analytical model of an adopted cable-stayed bridge is shown in Fig. 7. This model is based on the Ikuchi bridge which is one of the Simanami bridges connecting Onomichi City and Imabari City in Japan. Considering the symmetry of the bridge, the half model as shown in Fig. 8 was used. In particular, two types of cables were applied to this bridge, one is steel cables, another is CFRP cables.

The section modulus and material properties used in the analysis are summarized in Table 3[3) 4)]. The applied load is shown in Table 4[3)].

Fig. 7 Overall view of the cable-stayed bridge

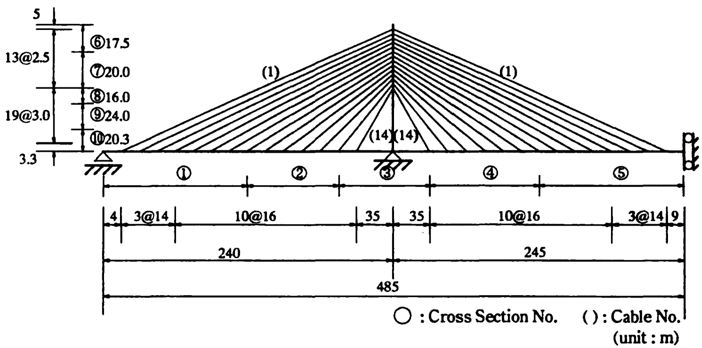


Fig. 8 Dimensions and boundary conditions of the half-model

In the previous analysis in Ref. 3), the cable prestresses has been determined in such a way that deflections do not occur at the anchorages of the cables in the main girder, when the dead load is applied to the analytical model.

Table 4 Applied load (dead load)

	Girder	Tower	Cable No.	Steel Cable	CFRP Cable
Dead Load (N/mm)	182.3	185.2	(1)	2.8655	0.1317
			(2)~(11)	1.9737	0.0878
			(12)~(14)	0.9604	0.0439

Table 3 Section modulus and material properties

	Cross Section No.	E (N/mm^2)	A (m^2)	I (m^4)	E_2 (N/mm^2)	η (year·N/mm^2)
Girder	①	2.06×10^5	1.302	2.258	-	-
	②	2.06×10^5	1.179	1.996	-	-
	③	2.06×10^5	1.449	2.365	-	-
	④	2.06×10^5	1.317	2.269	-	-
	⑤	2.06×10^5	1.045	1.767	-	-
Tower	⑥	2.06×10^5	0.640	4.538	-	-
	⑦	2.06×10^5	0.781	5.583	-	-
	⑧	2.06×10^5	0.800	5.818	-	-
	⑨	2.06×10^5	0.847	6.167	-	-
	⑩	2.06×10^5	0.996	6.754	-	-
	Cable No.					
Steel Cable	(1)	1.92×10^5	1.74×10^{-2}	2.40×10^{-5}	8.87×10^6	4.38×10^5
	(2)~(11)	1.92×10^5	1.20×10^{-2}	1.15×10^{-5}	8.87×10^6	4.38×10^5
	(12)~(14)	1.92×10^5	5.81×10^{-3}	2.69×10^{-6}	8.87×10^6	4.38×10^5
CFRP Cable	(1)	1.18×10^5	8.39×10^{-3}	5.60×10^{-6}	-	-
	(2)~(11)	1.18×10^5	5.59×10^{-3}	2.49×10^{-6}	-	-
	(12)~(14)	1.18×10^5	2.80×10^{-3}	6.22×10^{-7}	-	-

3.2 Results and Comments

Analytical results of the two types of cable-stayed bridges are shown in Figs. 9~11. As for the bridge with CFRP cables, the analysis was carried out until only 1,000 hours, because the experimental data over 1,000 hour are not yet available.

Fig. 9 shows the displacement of the center of the bridge. The horizontal axis is the time, and the vertical axis is the normalized displacements divided by the initial displacements. It is found that in case of the bridge with steel cables, the final displacement is about 2.5 times the initial displacement, and after 0.3 year, the displacement stabilizes. On the other hand, in case of the bridge with CFRP cables, it is found that the final displacement is more than 4.0 times the initial displacement. Therefore, from these results, steel cables can be considered better than the CFRP cables from the viewpoint of relaxation.

Secondly, the changes of the tensile force in the cable (1) of the side span as shown in Fig. 8 is shown in Fig. 10. The horizontal axis is the time, and the vertical axis, the normalized cable axial force divided by the initial cable axial force. It can be seen that in case of the bridge with steel cables the final normalized axial force will be almost 0.9957 after 0.3 year. On the other hand, in case of the bridge with CFRP cables the predicted value for the final normalized axial force ratio is about 0.994.

Fig. 11 illustrates the change of bending moment with the elapsed time. Vertical axis shows the normalized bending moments divided by the initial ones. It is understood from this figure that M/M_{t0} of the steel cable model converges into 1.40 during about 0.3 year. On the other hand, that of the CFRP cable model can be predicted to converge to 1.43.

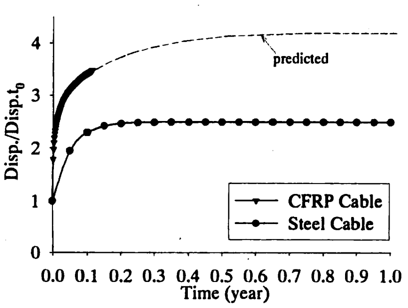


Fig. 9 Displacements at the center of the bridge

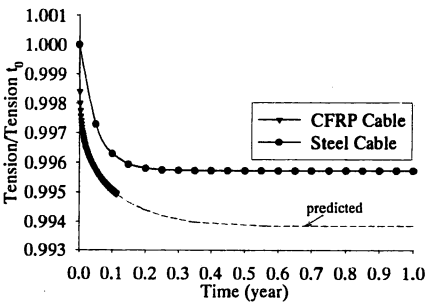


Fig. 10 Cable forces at the upper of the side span

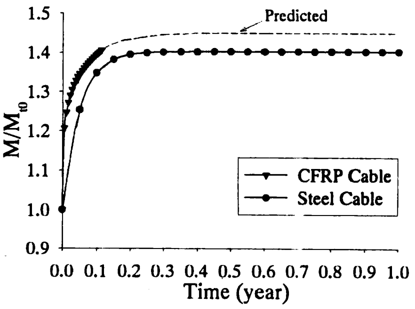


Fig. 11 Bending moments at the base of the tower

4. Concluding Remarks

In the present study, in order to investigate the long-term behavior of bridges considering visco-elastic behavior, the analytical program was developed. Analyzing the long-term behavior of two types of cable-stayed bridges, one with steel cables, another with CFRP cables by using this analytical program, its applicability to bridge structures was discussed. Concluding remarks and comments for future research needs obtained from this study are as follows:

(1) The long-term behavior analytical program for 2D framed structures considering visco-elastic behavior was developed. It was confirmed that the developed program is efficient.

(2) In the present study, the long-term behavior of a bridge with CFRP cables was investigated. However, due to the limitation of the experimental data on the relaxation rate, the bridge behavior at the final stage could not be analyzed. Therefore, in order to investigate the ultimate state of the bridge, long-term tension tests should be carried out.

(3) The visco-elastic behavior of cables can be considered to be very small. However, considering that the influence of concrete elements on the long-term behavior of the bridge structure cannot be neglected. Improvements in the program considering other materials such as concrete are, therefore, necessary.

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